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Monterey, California

THESIS

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2-DIMENSIONAL AXISYMMETRIC AND 3-DIMENSIONAL FINITE ELEMENT STRESS ANALYSIS OF THE LHA-1 CLASS SUPER-HEATER HEADER

by

Doyle R. Kitchin

March 1988

Thesis Advisor G. Cantin

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curity classification of this page

REPORT DOCUMENTATION PAGE

a Report Security Classification Unclassified		1b Restrictive Markings			
a Security Classification Authority		3 Distribution/Availability of Report Approved for public release; distribution is unlimited.			
b Declassification/Downgrading Schedule					
Performing Organization Report Number(s)		5 Monitoring Organization Report Number(s)			
a Name of Performing Organization Naval Postgraduate School	6b Office Symbol *(if applicable)* 69	7a Name of Monitoring Organization Naval Postgraduate School			
c Address *(city, state, and ZIP code)* Monterey, CA 93943-5000		7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000			
a Name of Funding/Sponsoring Organization	8b Office Symbol *(if applicable)*	9 Procurement Instrument Identification Number			
c Address *(city, state, and ZIP code)*		10 Source of Funding Numbers			
		Program Element No	Project No	Task No	Work Unit Accession No

1 Title *(include security classification)* 2-DIMENSIONAL AXISYMMETRIC AND 3-DIMENSIONAL FINITE ELEMENT STRESS ANALYSIS OF THE LHA-1 CLASS SUPERHEATER HEADER

2 Personal Author(s) Doyle R. Kitchin

3a Type of Report Master's Thesis	13b Time Covered From To	14 Date of Report *(year, month, day)* March 1988	15 Page Count 112

6 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

7 Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
ield	Group	Subgroup	Thermal Stress Analysis

19 Abstract *(continue on reverse if necessary and identify by block number)*

ADINA, a finite element program for automatic dynamic incremental nonlinear analysis, is used to conduct a stress analysis of the Tarawa class (LHA-1) superheater header. This investigation is sponsored by the Naval Sea Systems Command (NAVSEA) as a result of cracking in the superheater header tube attachment weld. A 2-dimensional solid axisymmetric finite element model was developed using both a coarse and fine mesh. Both pressure and thermally induced stresses were studied. A 3-dimensional solid finite element model was developed and a preliminary stress analysis conducted.

20 Distribution/Availability of Abstract ☒ unclassified/unlimited ☐ same as report ☐ DTIC users	21 Abstract Security Classification Unclassified	
22a Name of Responsible Individual G. Cantin	22b Telephone *(include Area code)* (408) 646-2364	22c Office Symbol 69Ci

D FORM 1473,84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

security classification of this page

Unclassified

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2-dimensional axisymmetric and 3-dimensional finite element stress analysis of the LHA-1 class superheater header

by

Doyle R. Kitchin
Lieutenant Commander, United States Navy
B.S.M.E., United States Naval Academy, 1976

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING
and
MECHANICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL
March 1988

ABSTRACT

ADINA, a finite element program for automatic dynamic incremental nonlinear analysis, is used to conduct a stress analysis of the Tarawa class (LHA-1) superheater header. This investigation is sponsored by the Naval Sea Systems Command (NAVSEA) as a result of cracking in the superheater header tube attachment weld. A 2-dimensional solid axisymmetric finite element model was developed using both a coarse and fine mesh. Both pressure and thermally induced stresses were studied. A 3-dimensional solid finite element model was developed and a preliminary stress analysis conducted.

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I. INTRODUCTION

The Tarawa (LHA-1) class amphibious assault ships have been experiencing numerous failures of their superheater header. The failures occur in the tube attachment weld. This is a relatively new class of ship and they are expected to be in commission for another twenty to thirty years. The solution of this problem is imperative to prevent the excessive down time experienced by these engineering plants.

A 2-dimensional solid axisymmetric finite element model was developed using ADINA. A study of the effect of different thermal gradients across the thickness of the header was conducted. The model yielded very different results dependent on the boundary conditions imposed. A discussion is made of the boundary conditions and the conclusion that a 3-dimensional model would more closely model the actual physical boundary conditions of this structure.

A 3-dimensional solid finite element model was developed. A discussion is made of the boundary conditions and a study is made of the internal pressure loading.

II. DESCRIPTION OF THE PROBLEM

NAVSEA has been conducting an extensive investigation to determine the cause for the weld joint cracking. The following list was provided by NAVSEA and is an analysis of weld joint cracking on the USS Tarawa (LHA-1):

- Linear defects were located by MT inspection in original fabrication welds and repair welds alike, including welds installed as recently as 1982.
- Predominant linear defect was the transverse weld crack, occurring singly and in multiples of two or more; crack indications ranged from 1/16 inch to 5/8 inch in length.
- Numerous linear indications were also found across the thin ligaments between welds in the A-to-D loop direction; cracks occurred singly and in multiples, and ranged in length from 1/16 inch to 3/4 inch.
- Predominant crack orientation was transverse to the longitudinal axis of the header; very few axially oriented indications were observed.
- Cracked welds in the inlet/outlet header were concentrated in the first and fourth passes.
- No apparent concentration of defects in the welds adjacent to the division plates (region of highest thermal gradient).
- The inlet/outlet header examined contained nearly 2-1/2 times as many weld joints with linear defects as did the intermediate header (32% of welds in no. 1 boiler inlet/outlet header vs. 13% of welds in no. 2 boiler intermediate header).
- Destructive analysis indicated the maximum crack depth to be approximately 5/32 inch, and the crack propagation mechanism to be fatigue at elevated temperature.

Figure 1 on page 3 and Figure 2 on page 4 are photographs taken by NAVSEA showing magnetic particle indications of the cracking. A more detailed description of this problem is given in [Ref. 1: pp. 10-15].

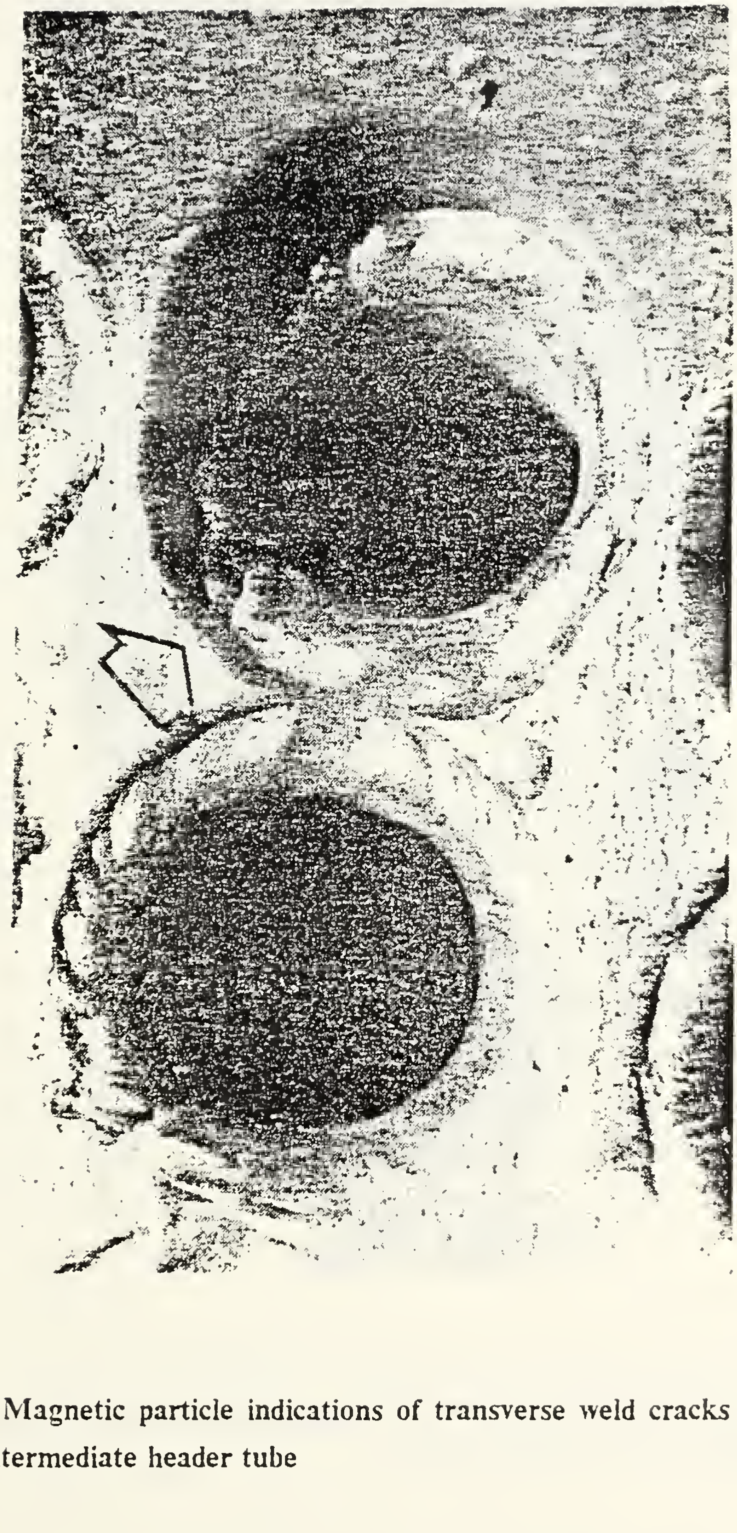


Figure 1. Magnetic particle indications of transverse weld cracks in no. 2 boiler intermediate header tube

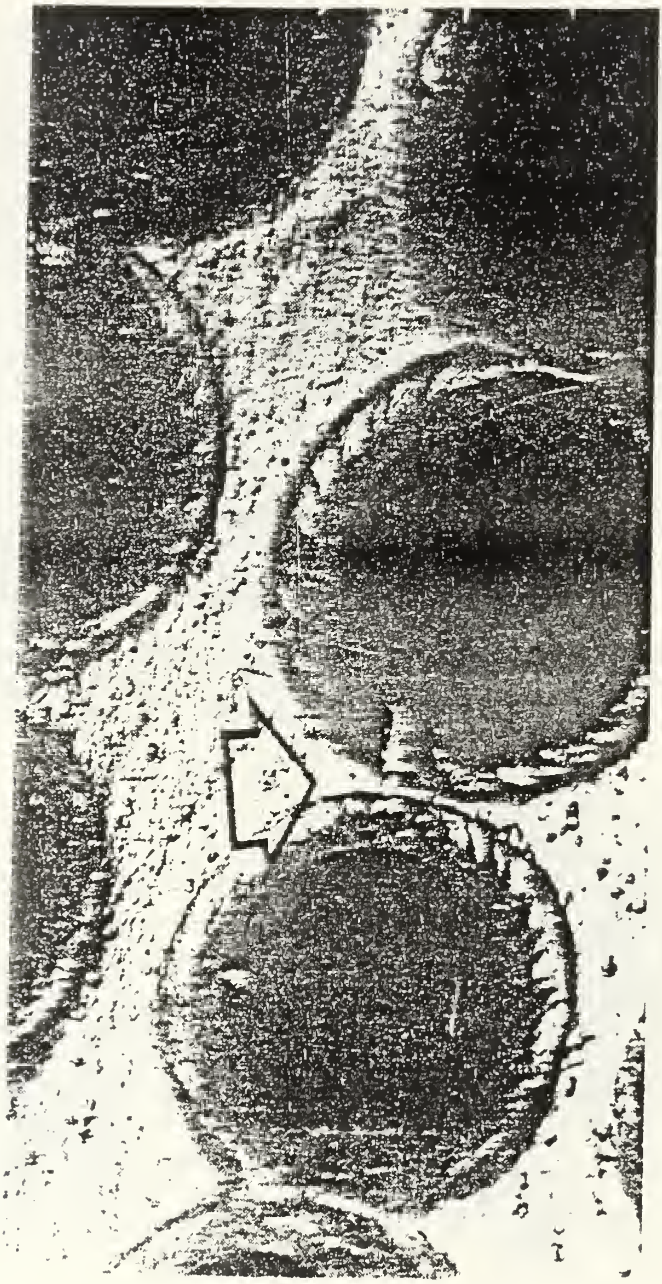


Figure 2. Magnetic particle indications of ligament cracks in no. 1 boiler inlet/outlet header tube attachment joints

III. DESCRIPTION OF ADINA

ADINA is a finite element program for automatic dynamic incremental nonlinear analysis. The ADINA system is composed of four main programs: ADINA-IN, ADINA, ADINA-PLOT and ADINAT. The 1984 version was used for this thesis. The sequence of execution of these programs is shown in Figure 3 on page 6 which is taken from [Ref. 2: p. 1-2].

A. GENERATION OF INPUT DATA

ADINA-IN generates the input data for ADINA or ADINAT. ADINA is used for displacement and stress analysis and ADINAT performs the temperature analysis. ADINA-IN can be run in an interactive or batch mode.

Coordinates can be input in a local or global coordinate system using cartesian, cylindrical or spherical coordinates. There are several automatic mesh generation methods available.

ADINA-IN has the ability to graphically check the model. All or part of the model can be drawn from any view desired, including element and nodal numbering. The LINES parameter described in [Ref. 2: p. 5.25-15] gives some ability to specify which lines on the model will be drawn. This allows an outline of the model to be drawn and the ability to check for missing elements.

The procedure for utilizing ADINA-IN to generate input data for ADINA on the VAX/VMS operating system is explained in Appendix A. The procedure for utilizing ADINA-IN to generate input data to solve the thermally induced stress problem is explained in Appendix B. The reverse Cuthill-McKee bandwidth optimization is used in generating the input file for ADINA.

B. POST-PROCESSING

ADINA-PLOT performs the post-processing of the output data from ADINA. It also has graphics capability, allowing a view of both the deformed and undeformed shapes. The deformed scale factor can be specified. ADINA-PLOT can also do vector plotting of the principal stresses.

Several listing options are available. Displacements or stresses for all or part of the model can be printed. Maximum values or results exceeding a specified value can also be listed.

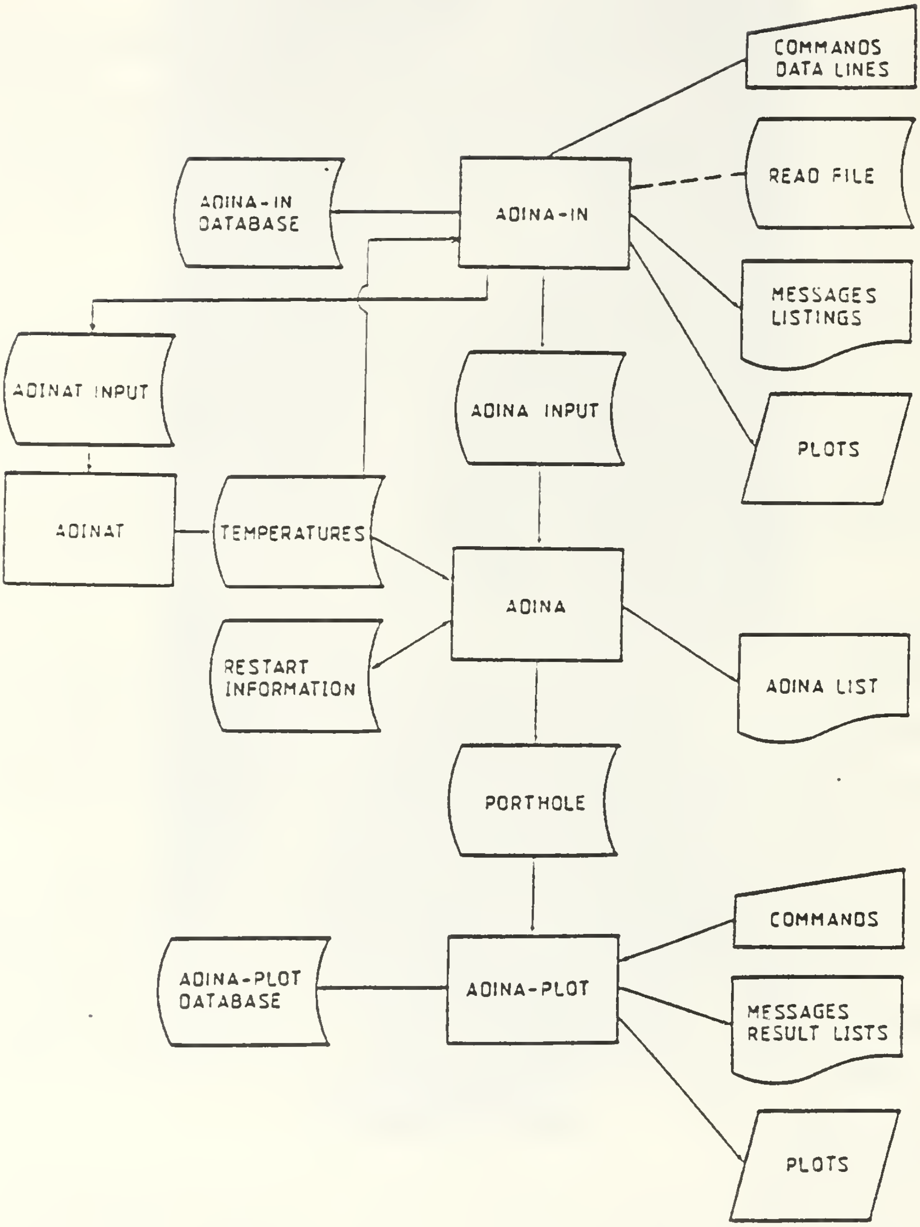


Figure 3. Sequence of execution of ADINA programs

The procedure for operating ADINA-PLOT on the VAX/VMS operating system is explained in Appendix C.

C. METHOD OF SOLUTION

ADINA uses isoparametric displacement based finite elements. The basic assumptions from [Ref. 3: p. 2.3-8] are:

for the coordinates

$$x = \sum_{i=1}^{q} h_i x_i \quad y = \sum_{i=1}^{q} h_i y_i \quad z = \sum_{i=1}^{q} h_i z_i \tag{3.1}$$

for the displacements

$$u = \sum_{i=1}^{q} h_i u_i \quad v = \sum_{i=1}^{q} h_i v_i \quad w = \sum_{i=1}^{q} h_i w_i \tag{3.2}$$

where:

- h_i(r,s,t) = the interpolation function corresponding to node i
- r,s,t = the isoparametric coordinates
- q = the number of element nodes
- x_i, y_i, z_i = nodal point coordinates
- u_i, v_i, w_i = nodal point displacements

ADINA uses the principle of virtual displacement to generate the equilibrium equations. The equilibrium equation as listed in [Ref. 4: p. 124] is:

$$K\,U = R \tag{3.3}$$

where:

- K = the element stiffness matrix
- U = the unknown nodal point displacements
- R = the load vector which includes body forces, surface forces, initial stresses and concentrated loads.

The development of the stiffness matrix for the isoparametric element is given in [Ref. 4: pp. 203-204]:

$$K = \int_V B^T C B \, dV \tag{3.4}$$

where:

- B = the strain-displacement matrix
- C = the elasticity matrix

In terms of the isoparametric coordinates:

$$dV = \det(J) \, dr \, ds \, dt \tag{3.5}$$

where:

- det(J) = the determinant of the Jacobian operator

The stresses are calculated using the strains at the point of interest. The basic relationships used are given in [Ref. 4: p. 123]:

$$\varepsilon = B \, U \tag{3.6}$$

$$\tau = C \, \varepsilon \tag{3.7}$$

where:

- ε = the element strain matrix
- τ = the element stress matrix

The element matrices are calculated using Gauss numerical integration. A (3x3x3) integration order is utilized as specified in [Ref. 3 : p. 2.3-16].

D. AXISYMMETRIC PROBLEM

The basic assumptions for the axisymmetric element are listed in [Ref. 3: p. 2.2-4]:

$$\varepsilon_{xx} = u/y \qquad (x \textit{ is the hoop direction}) \tag{3.8}$$

$$\tau_{xy} = \tau_{xz} = 0 \qquad (y \textit{ is the radial direction}) \tag{3.9}$$

If the loading is also axisymmetric, a 2-dimensional analysis of a unit radian of the structure will provide the complete stress and strain distributions. This greatly reduces the computational time compared to a 3-dimensional analysis.

E. CONTACT SURFACES

ADINA allows the specification of contact surfaces in the development of the model. Contact surfaces are defined in [Ref. 3: p. 4.1-1] as surfaces that are initially in contact, or are anticipated to come into contact during the response solution.

The contact surface problem is a nonlinear analysis. After each equilibrium iteration, the segment contact force is evaluated from the nodal forces. A contactor segment is shown in Figure 4 on page 10. The conditions of either tension release, sliding or sticking are determined for each segment. The basic equations are given in [Ref. 3: p. 4.2-3]. Tension release occurs if:

$$\vec{\eta}.\vec{T}_n^j < 0 \qquad (3.10)$$

where:

- $\vec{\eta}$ = the inward normal vector to segment j as shown in Figure 4 on page 10
- $\vec{T}_n^j$ = the normal contact force for segment j

Tension release means the surfaces are not in contact.

If the surfaces are in contact the condition of sliding or sticking is determined by using the friction law. Sticking occurs if:

$$\vec{T}_t^j < \mu \vec{T}_n^j \qquad (3.11)$$

where:

- $\vec{T}_t^j$ = the tangential contact force for segment j
- μ = the coefficient of friction

Sliding occurs if:

$$\vec{T}_t^j > \mu \vec{T}_n^j \qquad (3.12)$$

The nodal forces are calculated as the consistent nodal loads which correspond to the tangential and normal forces of the segment.

F. THERMAL ANALYSIS

ADINAT uses isoparametric finite element discretization. The basic assumptions from [Ref. 5: p. 11] are:

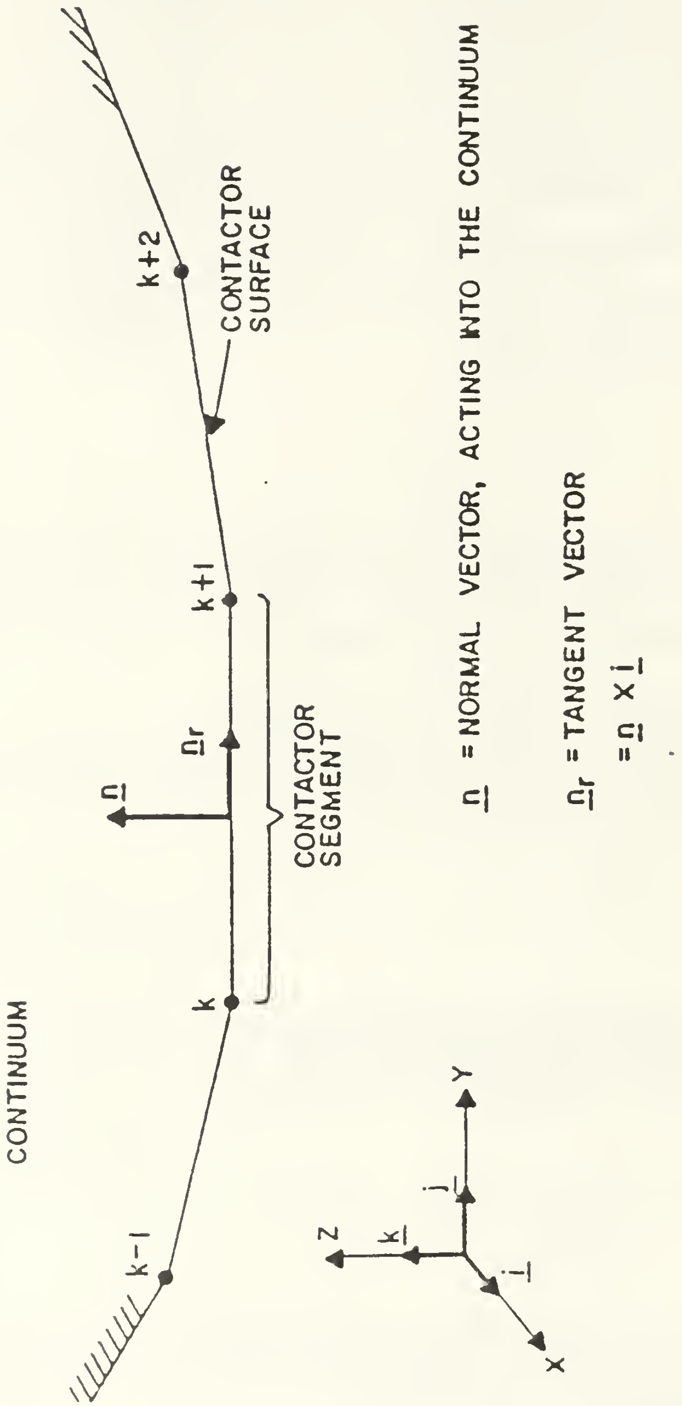


Figure 4. Contact surface contactor segment

$$x = \sum_{i=1}^{N} h_i x_i \quad y = \sum_{i=1}^{N} h_i y_i \quad z = \sum_{i=1}^{N} h_i z_i \tag{3.13}$$

and:

$$t + \Delta t_\theta = \sum_{i=1}^{N} h_i t + \Delta t_{\theta\,\mathrm{i}} \quad t_\theta = \sum_{i=1}^{n} h_i t_{\theta\,\mathrm{i}} \quad \Delta\theta = \sum_{i=1}^{n} h_i \Delta\theta_i \tag{3.14}$$

where:

- h_i = the element interpolation function
- N = the number of nodal points
- x_i, y_i, z_i = coordinates of the nodal point i
- $t + \Delta t_{\theta\,\mathrm{i}}$ = the temperature of nodal point i at time $t + \Delta t$
- $t_{\theta\,\mathrm{i}}$ = the temperature of nodal point i at time t
- $\Delta\theta_i$ = the temperature increment at nodal point i

The interpolation and substitution of these equations into the general incremental heat flow equilibrium equations yield the finite element equations.

G. VERIFICATION

Part of the installation process of a finite element code is the verification of the code. This is done by modeling a problem for which the results are known and comparing the results.

Three verifications are included in this thesis. The solution of a cantilever beam problem is compared with classical beam theory in Appendix D. The thermal stresses in an annular disk are compared with classical disk theory in Appendix E. The temperature distribution in a chimney is compared with a verified finite difference solution in Appendix F. The last two problems were chosen because of their similarity to the problem addressed in this thesis. In each case ADINA yielded excellent results.

IV. 2-DIMENSIONAL SOLID AXISYMMETRIC FINITE ELEMENT MODEL

This problem was originally modeled by Lieutenant Jon W. Kaufmann, United States Navy, in [Ref. 1]. The initial attempt of this thesis was to duplicate his model.

A. INITIAL MODEL DEVELOPMENT

NAVSEA provided a cross section drawing of the superheater header as illustrated in Figure 5 on page 13. They also provided a detail of the superheater header tube attachment weld joint in Figure 6 on page 14. The same geometry of the weld as developed in [Ref. 1: p. 18] was utilized and is illustrated in Figure 7 on page 15.

A nine-node plane axisymmetric element was used. This element is similar to the one used in [Ref. 1: p. 29].

A coarse and fine mesh were developed in order to do a study on convergence. The coarse mesh has 64 elements and 292 nodes. The model is shown in Figure 8 on page 16. A close-up of the weld is shown in Figure 9 on page 17, listing element numbers. The fine mesh has 224 elements and 1095 nodes and is illustrated in Figure 10 on page 18. The weld area is shown in Figure 11 on page 19.

The same boundary conditions stated in [Ref. 1: p. 30] were applied. The right hand side of the model was fixed as illustrated in Figure 12 on page 20. A frictional surface was applied between the tube and the header. The nodes on the boundary were constrained together in the y direction but allowed to move with respect to each other in the z direction. This is in effect applying a contact surface with the coefficient of friction equal to zero.

B. LOAD CONDITIONS

The same load conditions were applied as developed in [Ref. 1: pp. 38-42].

1. Load condition no. 1 - Internal pressure load

Load condition no. 1 consisted of an internal pressure of 700 psi applied at all nodes located on the inside of the tube and header. This corresponds to the full rating of the boiler. This loading is illustrated in Figure 13 on page 21.

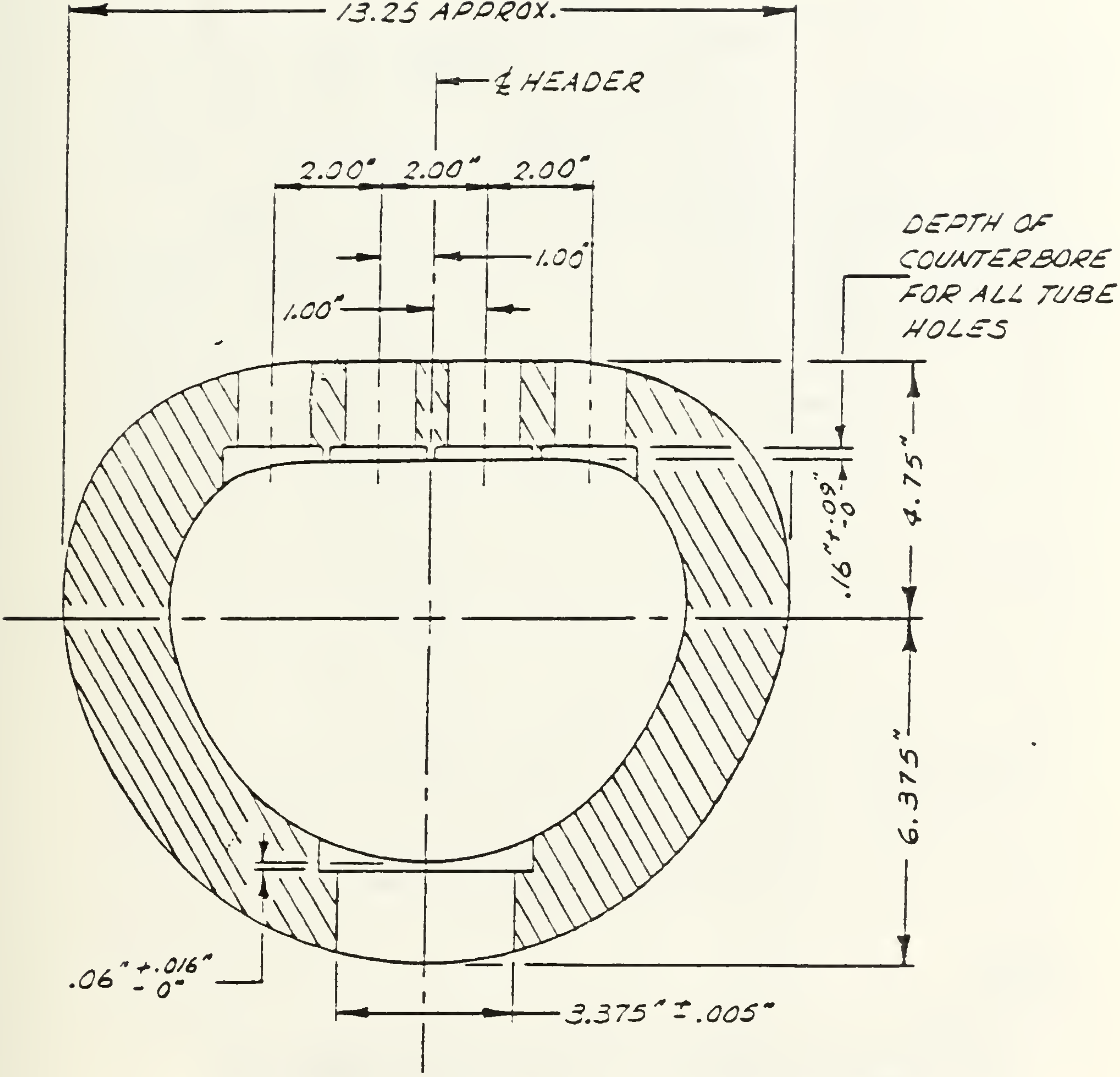
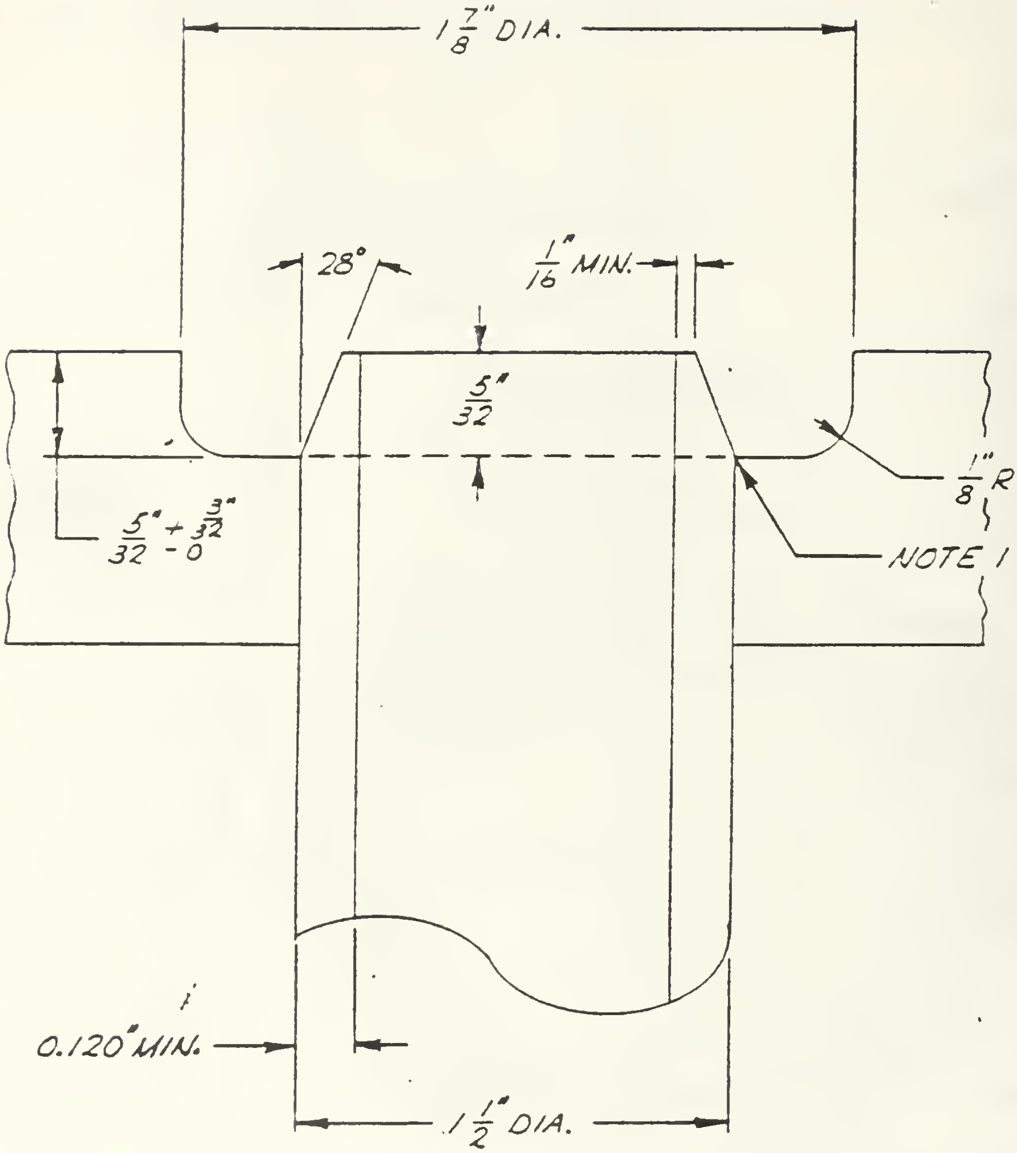


Figure 5. Cross sectional view of the superheater header



NOTE:

1. TUBE IS POSITIONED SUCH THAT BASE OF TUBE CHAMFER IS FLUSH WITH SQUARE CORNER AT BOTTOM OF COUNTERBORE AS SHOWN

Figure 6. Detail of the attachment weld joint

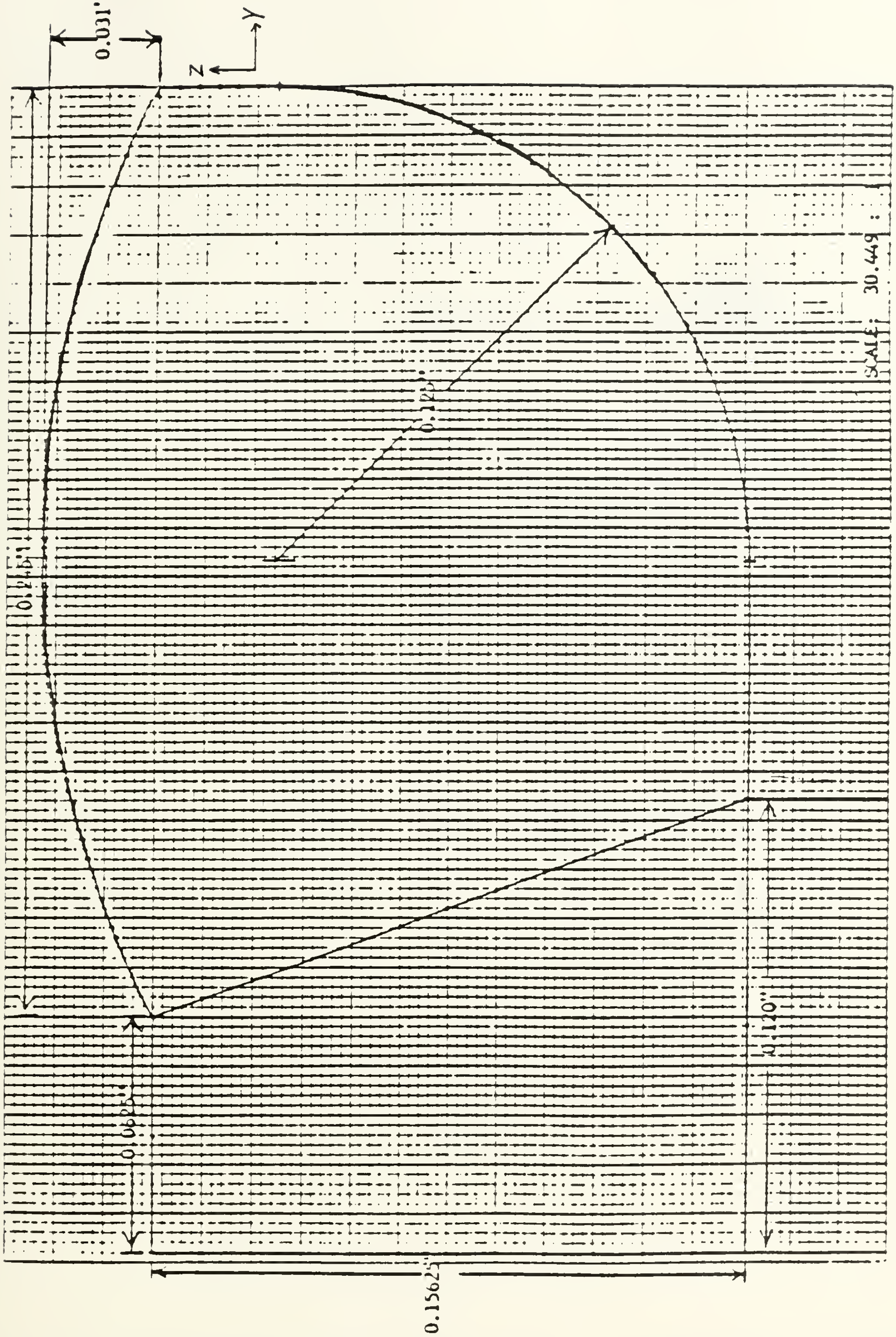


Figure 7. Geometry of the weld

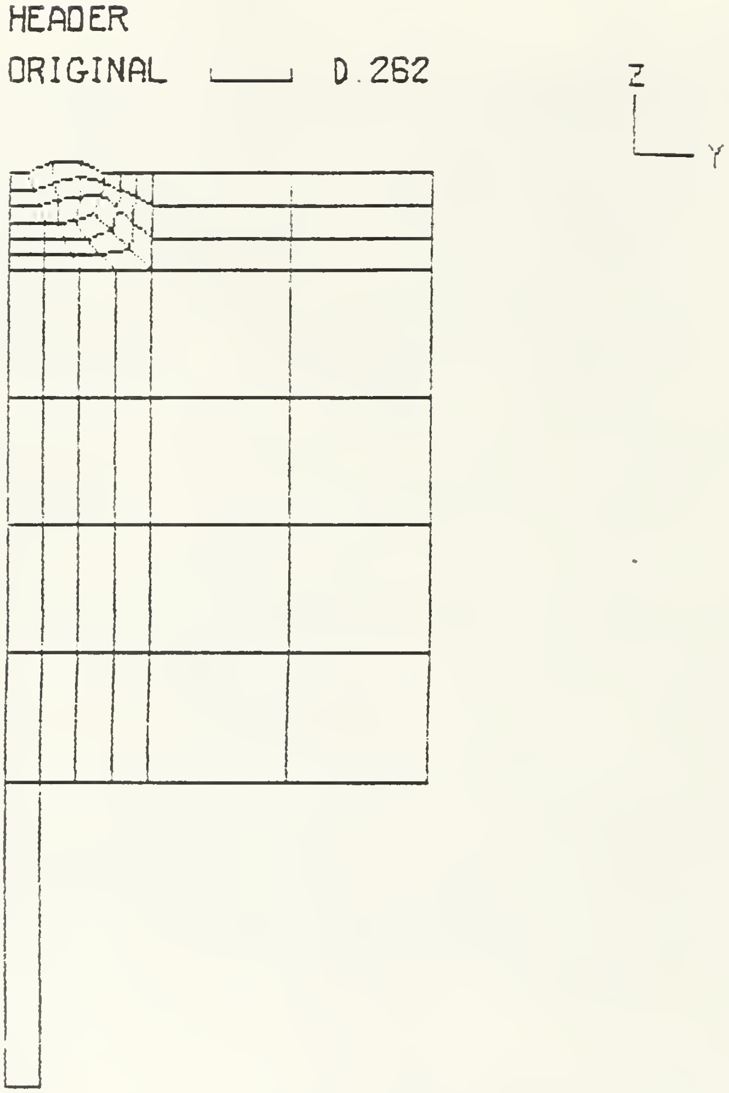


Figure 8. Coarse mesh

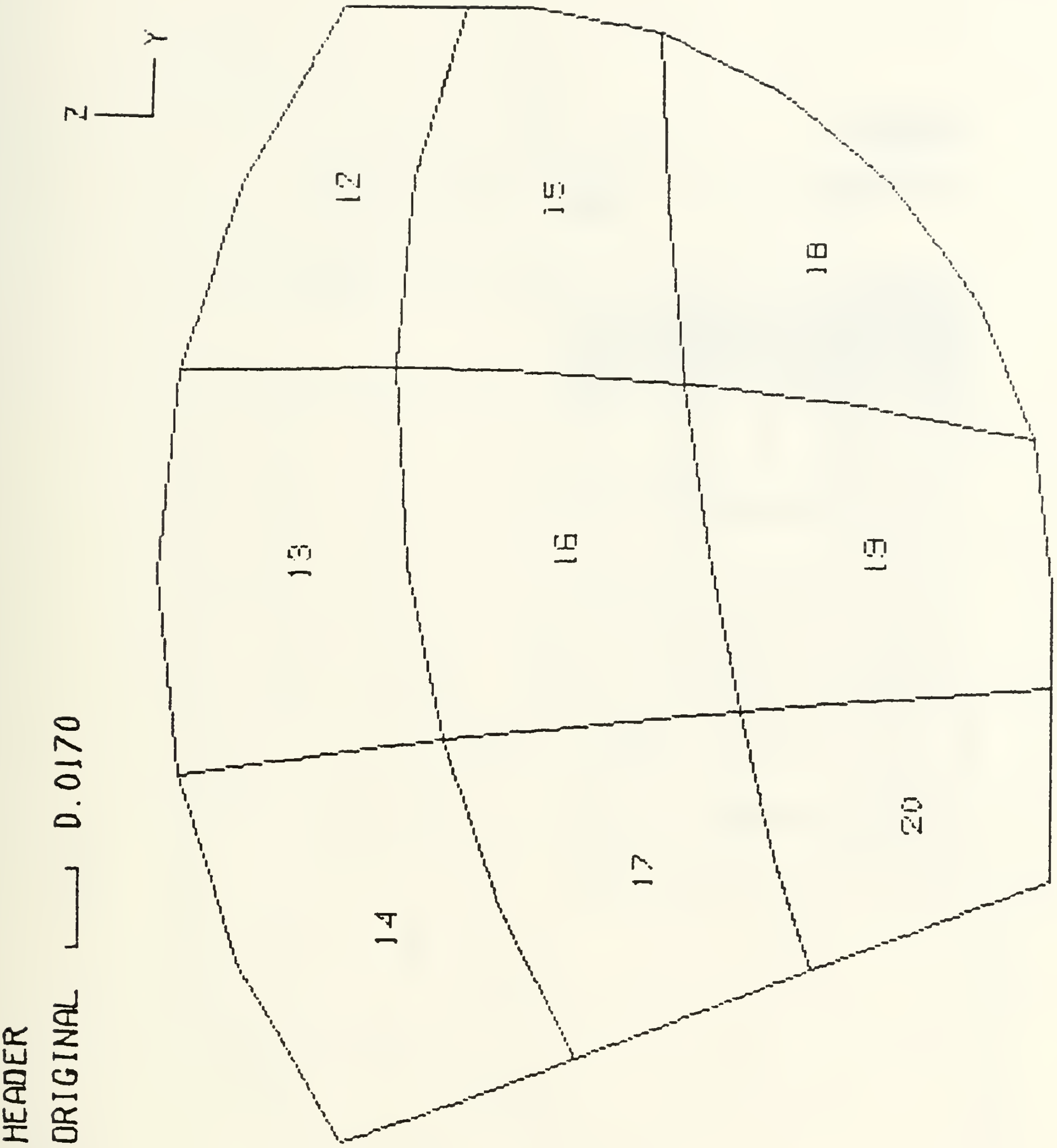


Figure 9. Close-up of the weld area, coarse mesh

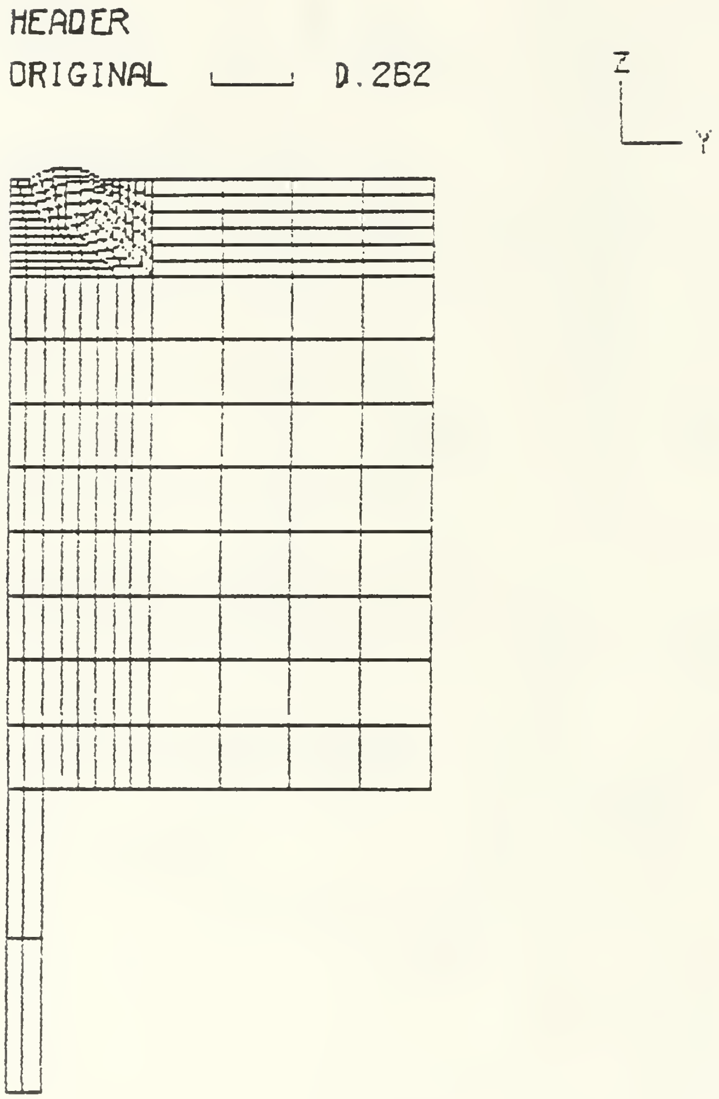


Figure 10. Fine mesh

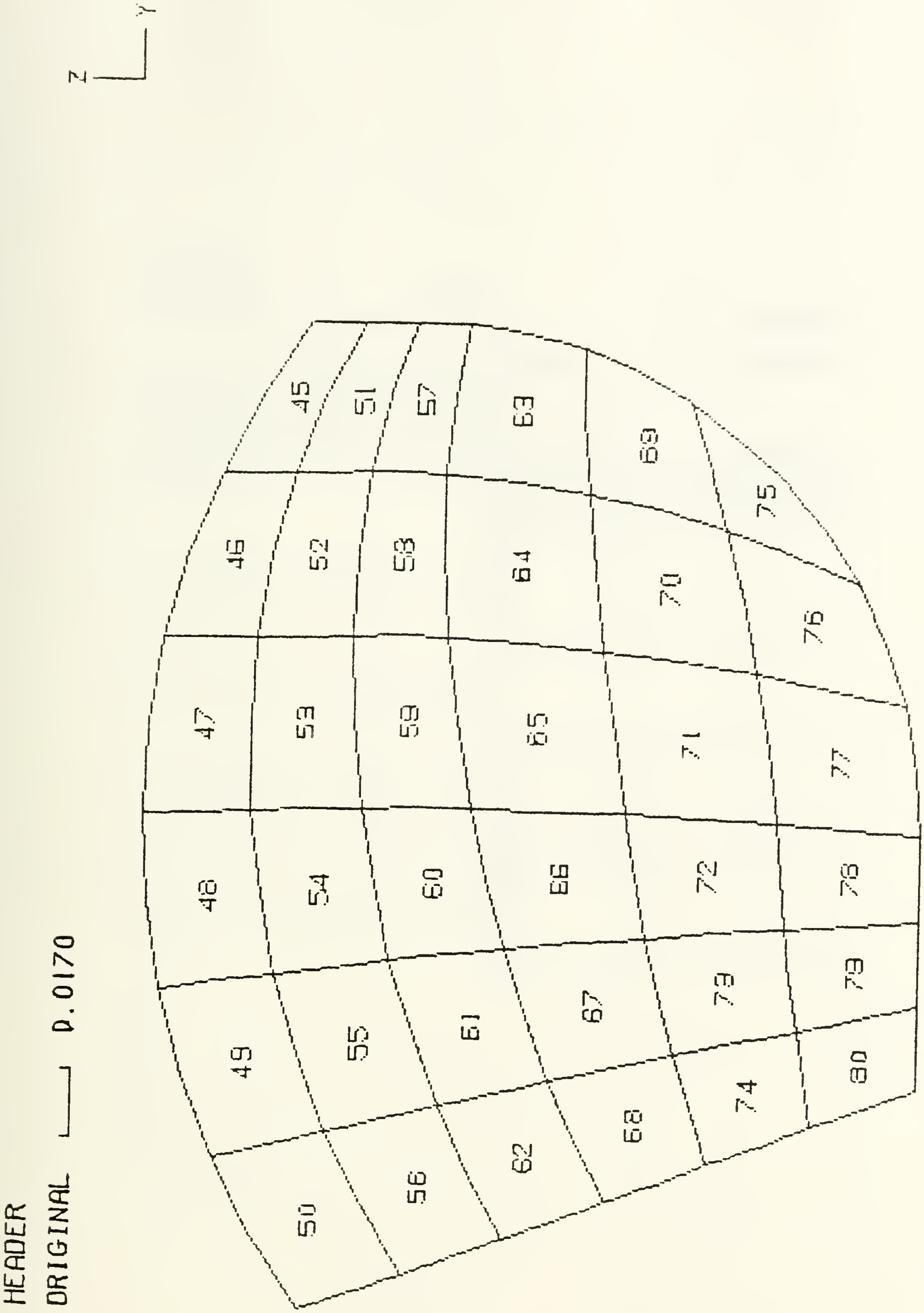


Figure 11. Close-up of the weld area, fine mesh

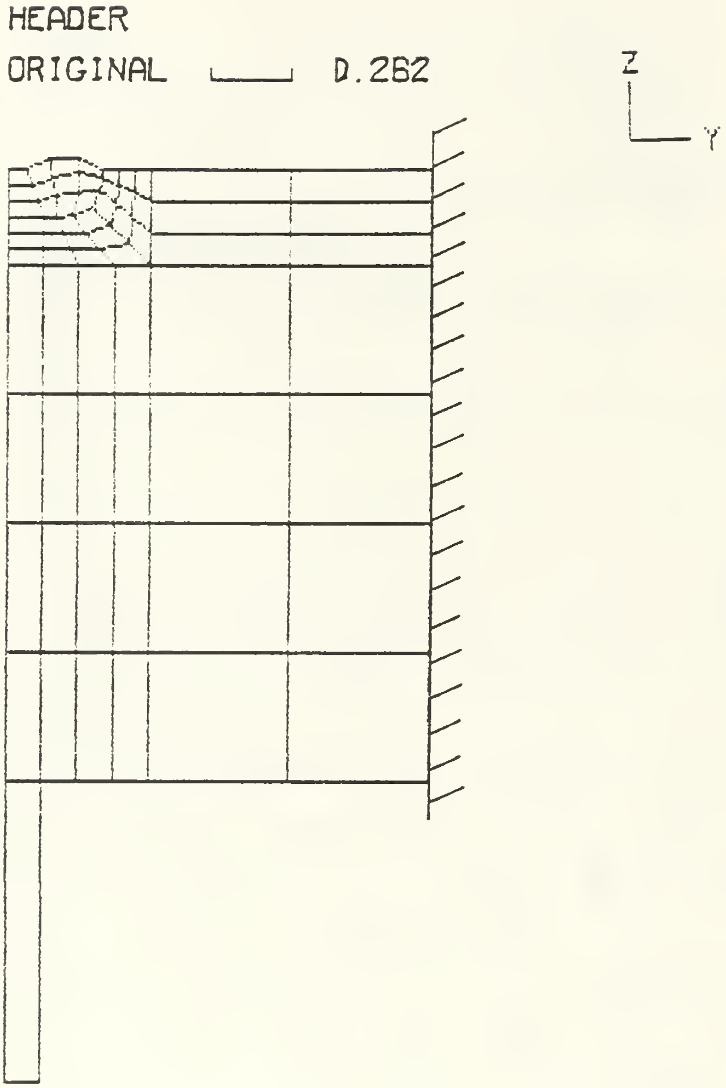


Figure 12. Fixed boundary conditions

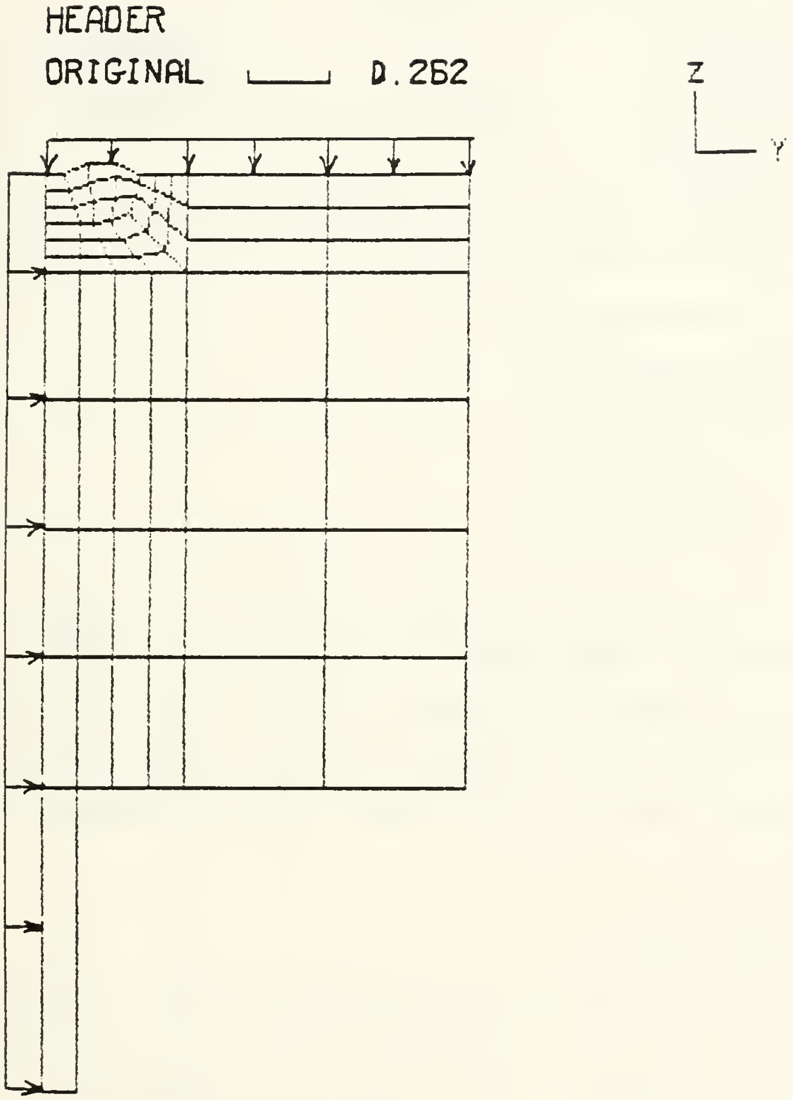


Figure 13. Load condition no. 1

2. Load condition no. 2 - Longitudinal tube load

The force per radian is 152 lbf. The coarse model uses the same consistent loading as [Ref. 1: p. 40]. The load was applied to the bottom element of the tube, on nodes 85, 68 and 87 as indicated in the following list:

- $F_{85} = F' \, (1/6) = 25.3 \, (Lb_f)$
- $F_{68} = F' \, (2/3) = 101.3 \, (Lb_f)$
- $F_{87} = F' \, (1/6) = 25.3 \, (Lb_f)$

This is illustrated in Figure 14 on page 23. The consistent loading for the fine mesh was applied to nodes 85, 240, 239, 238 and 87 as follows:

- $F_{85} = F' \, (1/12) = 12.66666666 \, (Lb_f)$
- $F_{240} = F' \, (1/3) = 50.66666666 \, (Lb_f)$
- $F_{239} = F' \, (1/6) = 25.33333333 \, (Lb_f)$
- $F_{238} = F' \, (1/3) = 50.66666666 \, (Lb_f)$
- $F_{87} = F' \, (1/12) = 12.66666666 \, (Lb_f)$

The consistent loading for the fine mesh is illustrated in Figure 15 on page 24.

3. Load condition no. 3 - Thermal load

The thermal load consists of maintaining a constant temperature of 350 degrees F at the interior nodes of the tube and header. A temperature gradient of 100 degrees F is applied to the right hand side of the model. This load condition is shown in Figure 16 on page 25.

C. MATERIAL PROPERTIES

The same material properties were used as listed in [Ref. 1: p. 38]. Young's Modulus (E) equals 29,600,000 psi, the coefficient of thermal expansion (α) equals .0000065 in/in/°F and Poisson's ratio (v) equals .3. The material of the tube and header is 2.25% chromium, 1% molybdenum steel (ASTM grade 22). The weld was assumed to have the same properties as the tube and header.

D. COMPARISON OF RESULTS

The original and deformed shapes for load conditions 1, 2 and 3 for the coarse mesh are shown in Figure 17 on page 26, Figure 18 on page 27, and Figure 19 on page 28. The results for the fine mesh are shown in Figure 20 on page 29, Figure 21 on page 30, and Figure 22 on page 31. The maximum stresses in the weld for the coarse and fine

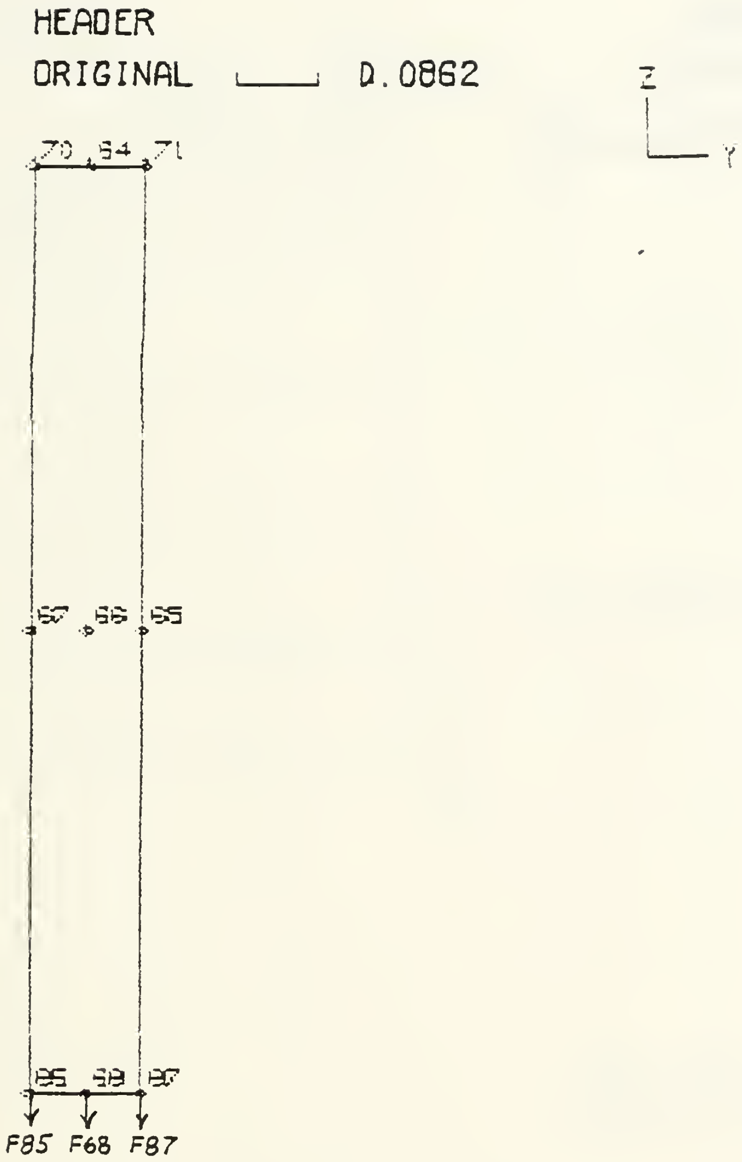


Figure 14. Load condition no. 2, coarse mesh

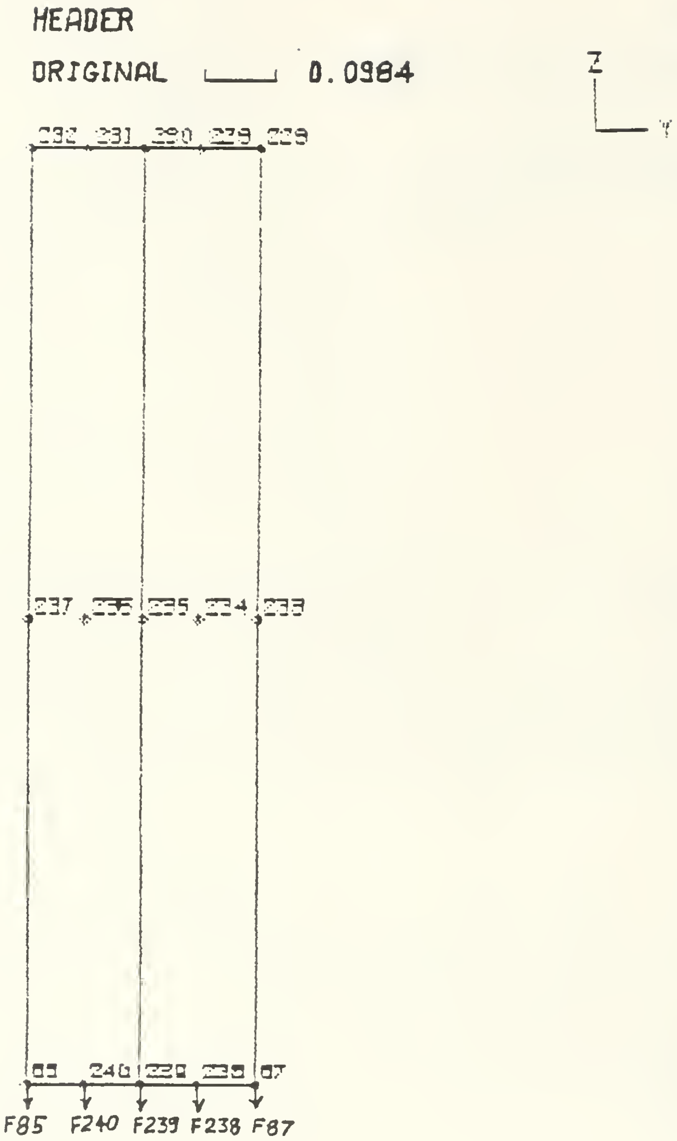


Figure 15. Load condition no. 2, fine mesh

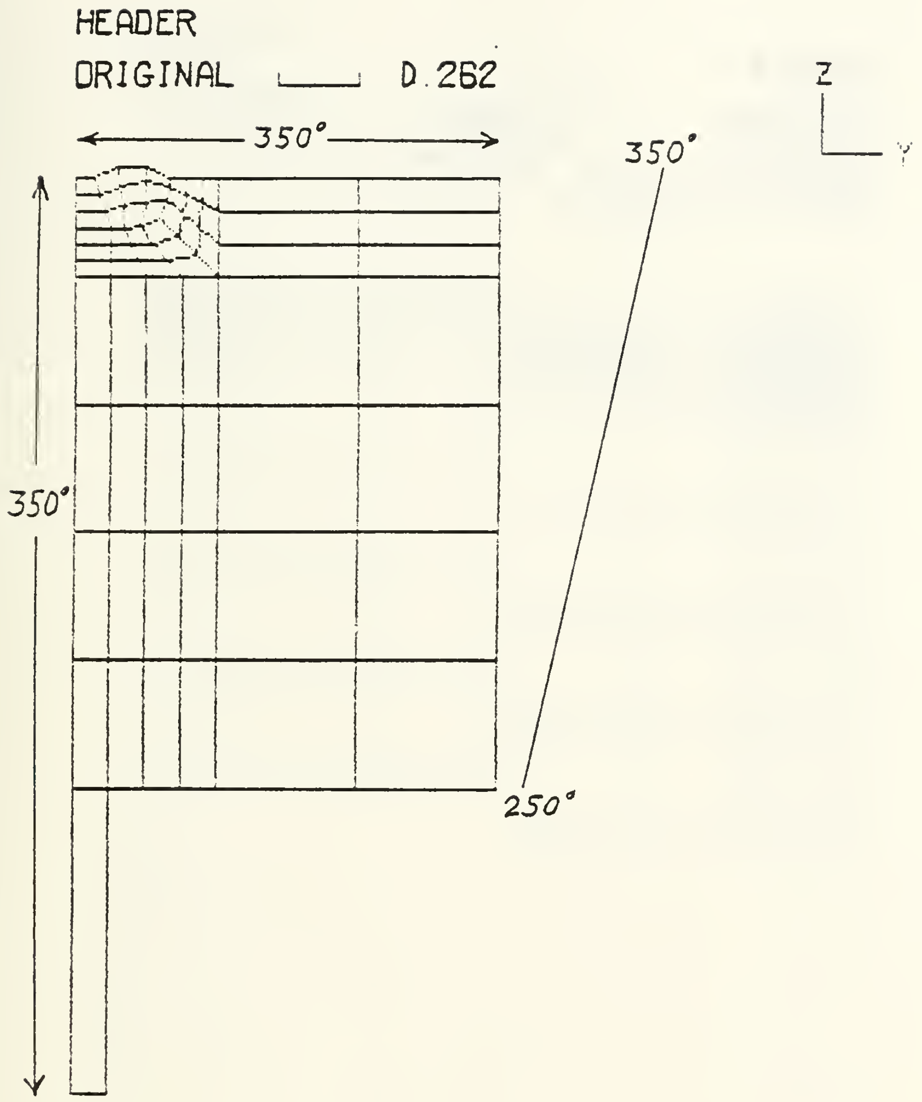


Figure 16. Load condition no. 3

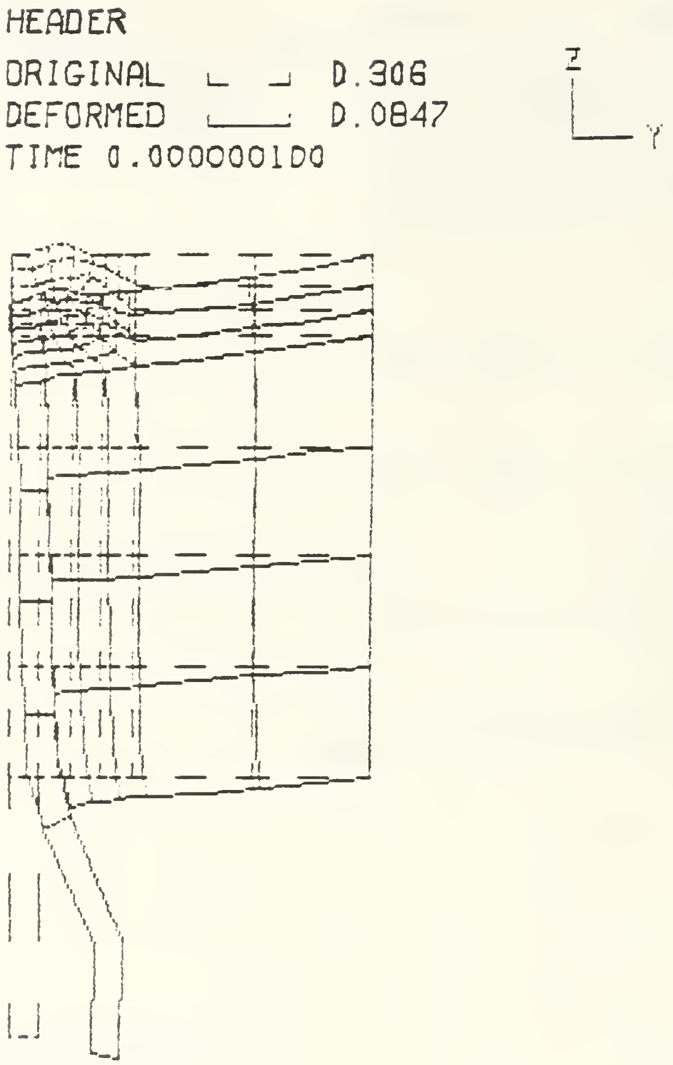


Figure 17. Original and deformed shape of coarse mesh for load condition no. 1

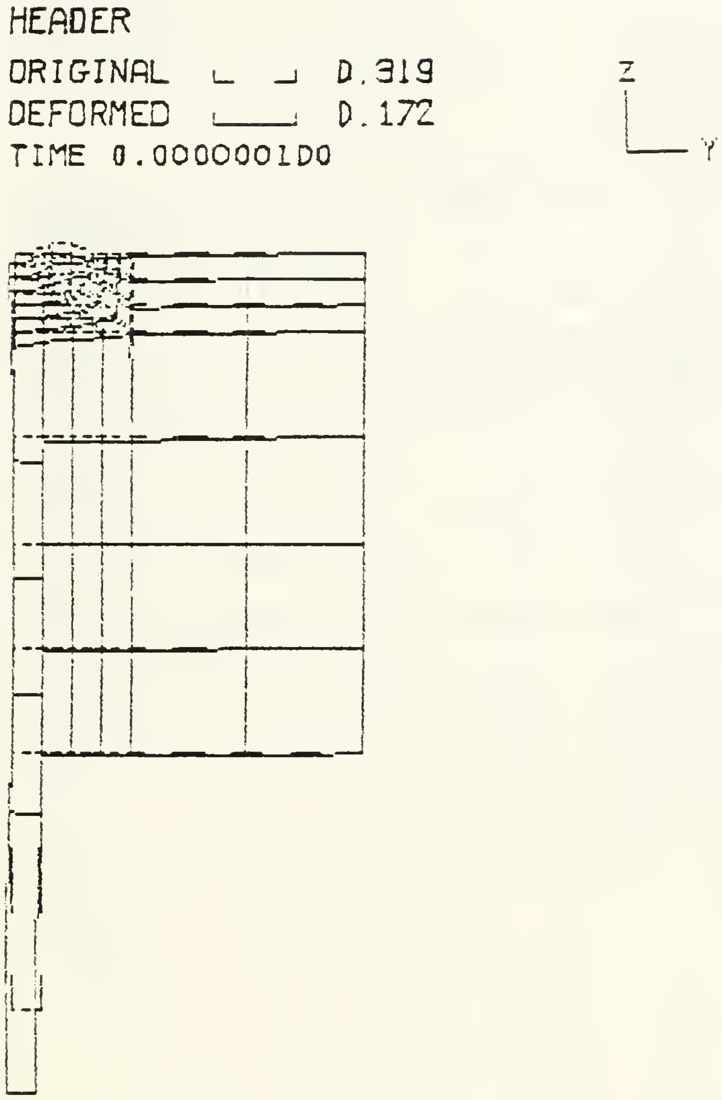


Figure 18. Original and deformed shape of coarse mesh for load condition no. 2

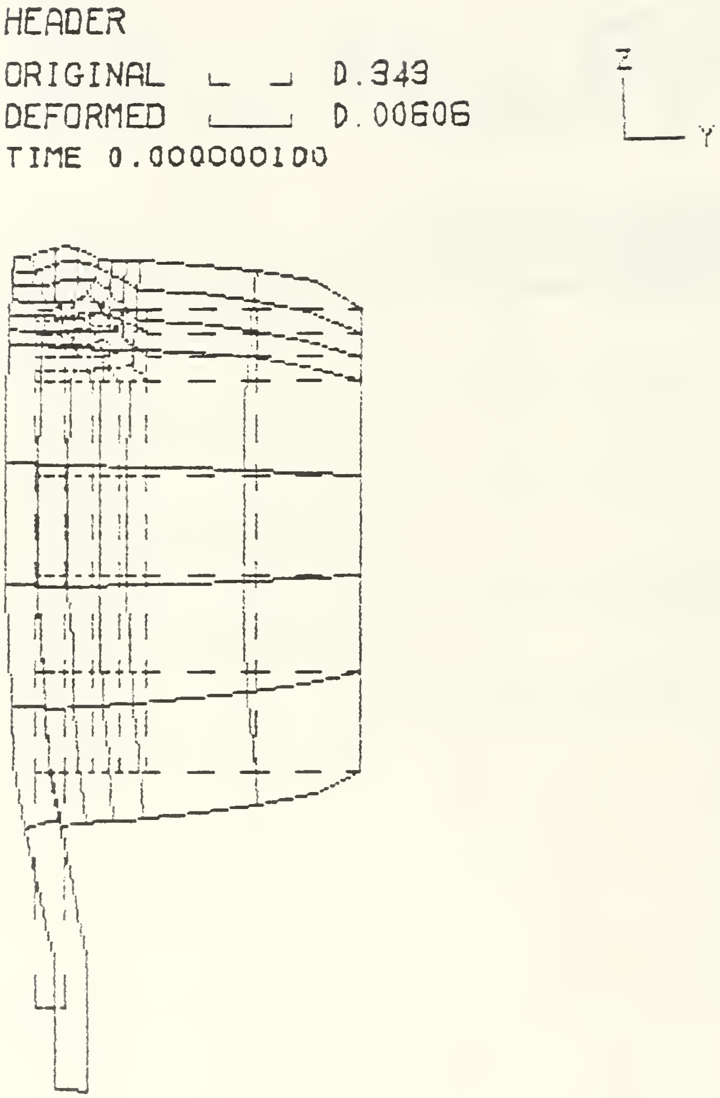


Figure 19. Original and deformed shape of coarse mesh for load condition no. 3

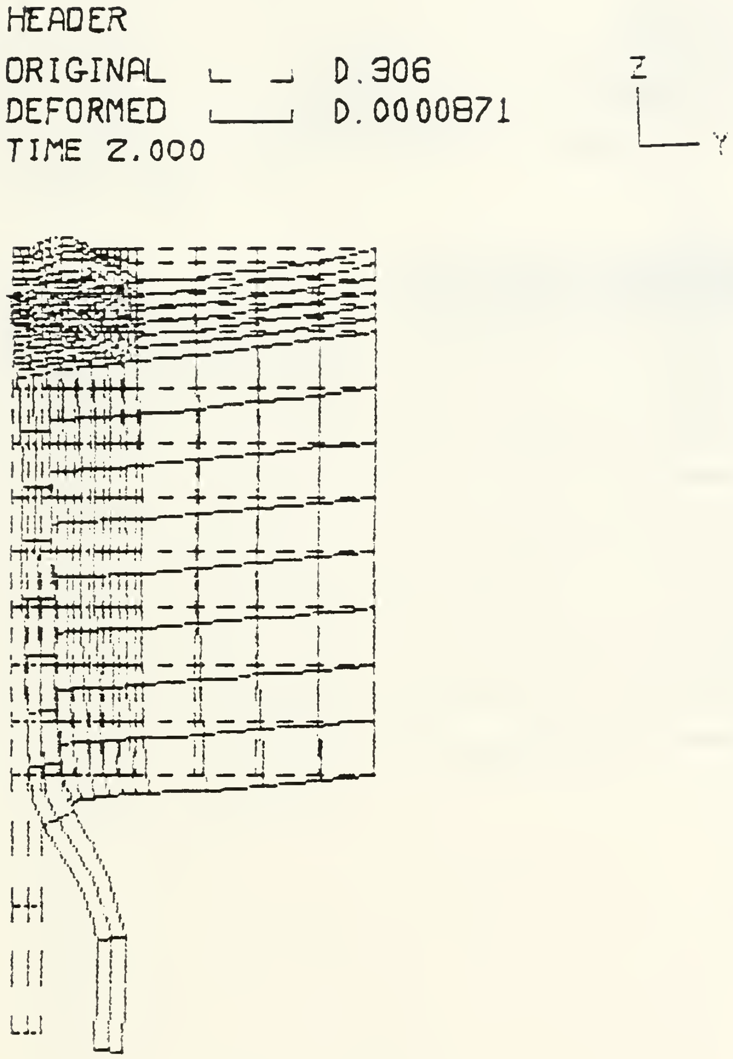


Figure 20. Original and deformed shape of fine mesh for load condition no. 1

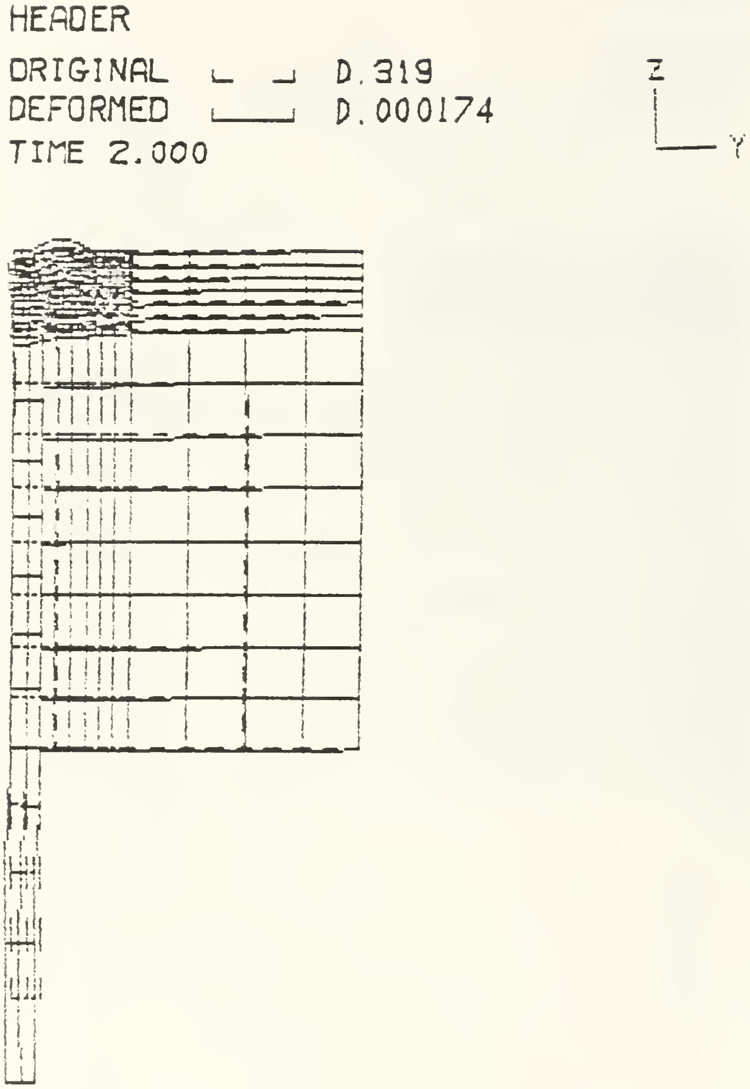


Figure 21. Original and deformed shape of fine mesh for load condition no. 2

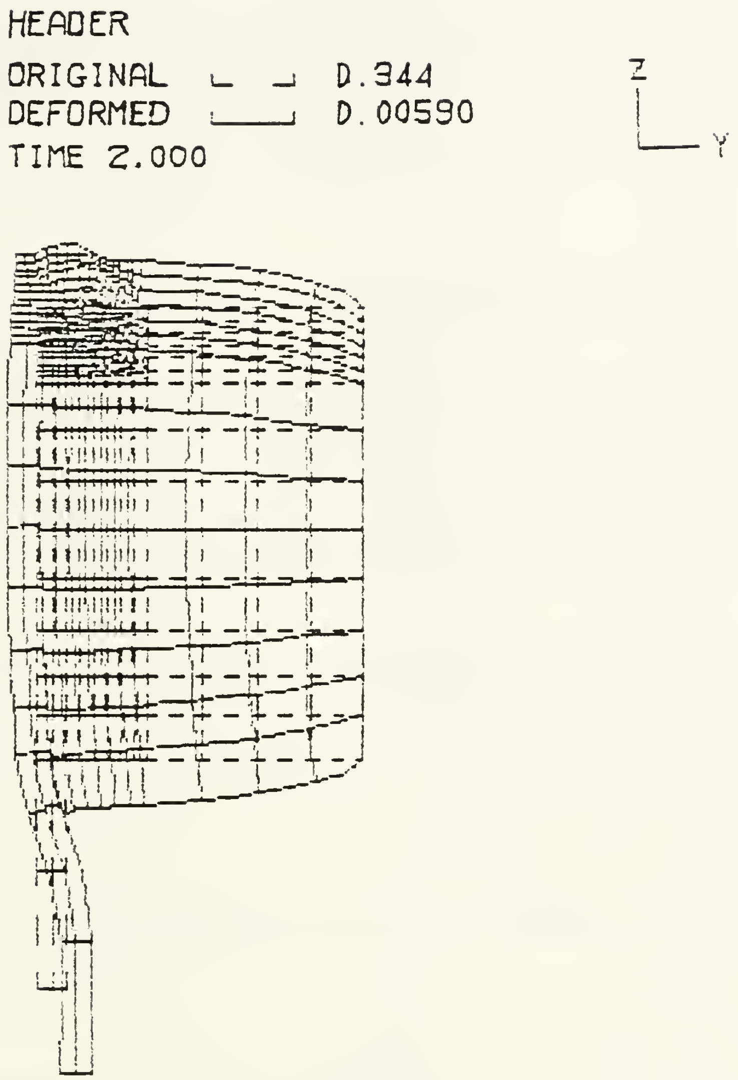


Figure 22. Original and deformed shape of fine mesh for load condition no. 3

mesh are listed in Table 1 and Table 2. For the axisymmetric problem, σ_{xx} is the hoop stress, σ_{yy} is the radial stress, and σ_{zz} is the longitudinal stress.

Table 1. MAXIMUM STRESSES FOR THE COARSE MESH

Stresses	Load Condition No. 1	Load Condition No. 2	Load Condition No. 3
σ_{xx} (psi)	-.636767E+03	-.509766E+03	-.135183E+06
σ_{yy} (psi)	-.661331E+03	-.370531E+03	-.466026E+05
σ_{zz} (psi)	-.742839E+03	-.116857E+03	-.559437E+04
σ_{yz} (psi)	.120933E+03	.332004E+03	.134600E+05

Table 2. MAXIMUM STRESSES FOR THE FINE MESH

Stresses	Load Condition No. 1	Load Condition No. 2	Load Condition No. 3
σ_{xx} (psi)	-.649740E+03	-.534142E+03	-.136960E+06
σ_{yy} (psi)	-.659697E+03	.503587E+03	-.555045E+05
σ_{zz} (psi)	-.753965E+03	-.145094E+03	-.980113E+04
σ_{yz} (psi)	.136478E+03	.372948E+03	.193084E+05

The magnitude and direction of the principal stresses for the coarse and fine mesh, in the area of the weld, are listed in Table 3 and Table 4. A vector plot of the principal stresses of the coarse and fine mesh for load condition no. 3 is shown in Figure 23 on page 34 and Figure 24 on page 35.

Table 3. PRINCIPAL STRESSES FOR THE COARSE MESH

Element	P1 (psi)	P2 (psi)	Angle ($^{\circ}F$)
12	-.1594E+03	-.3422E+05	74.57
13	0.1352E+04	-.1820E+05	85.39
14	0.2802E+03	-.1413E+05	94.46
15	0.9153E+03	-.3779E+05	86.39
16	0.3717E+04	-.2807E+05	86.38
17	0.2304E+04	-.2084E+05	86.18
18	0.1716E+04	-.3808E+05	88.03
19	0.3323E+04	-.3259E+05	87.72
20	0.3103E+04	-.2530E+05	86.98

Table 4. PRINCIPAL STRESSES FOR THE FINE MESH

Element	P1 (psi)	P2 (psi)	Angle (°*F*)
45	-.8641E+03	-.4057E+05	67.64
46	.8286E+03	-.2143E+05	73.66
47	.8814E+03	-.1572E+05	82
48	.6244E+03	-.1315E+05	90.31
49	.2067E+03	-.1219E+05	98.49
50	-.5970E+03	-.1293E+05	103.33
51	-.1553E+04	-.4200E+05	80.67
52	.2516E+04	-.3006E+05	79.02
53	.2590E+04	-.2272E+05	82.48
54	.2192E+04	-.1923E+05	86.37
55	.1592E+04	-.1725E+05	89.20
56	.2959E+03	-.1531E+05	88.85
57	-.2147E+04	-.4153E+05	85.36
58	.2898E+04	-.3440E+05	84.10
59	.3626E+04	-.2802E+05	84.60
60	.3324E+04	-.2402E+05	85.88
61	.2581E+04	-.2107E+05	86.41
62	.1310E+04	-.1789E+05	86.05
63	-.1468E+04	-.4044E+05	87.31
64	.2494E+04	-.3631E+05	87.32
65	.3856E+04	-.3161E+05	86.70
66	.3772E+04	-.2755E+05	86.46
67	.3107E+04	-.2403E+05	86.19
68	.2107E+04	-.2036E+05	85.89
69	-.1507E+02	-.3976E+05	87.96
70	.2439E+04	-.3685E+05	88.22
71	.3705E+04	-.3322E+05	87.71
72	.3793E+04	-.2956E+05	87.17
73	.3364E+04	-.2615E+05	86.76
74	.2660E+04	-.2254E+05	86.44
75	.1317E+04	-.3915E+05	88.01
76	.2801E+04	-.3685E+05	88.09
77	.3636E+04	-.3375E+05	97.90
78	.3742E+04	-.3055E+05	87.62
79	.3503E+04	-.2759E+05	87.37
80	.3035E+04	-.2437E+05	87.13

The maximum hoop stress listed in [Ref. 1: pp. 39-40] for load condition no. 1 is .69 (ksi) and the maximum hoop stress for load condition no. 2 is .96 (ksi). Those results compare favorably with the results shown here from ADINA. [Ref. 1: p. 42] indicates the maximum hoop stress for load condition no. 3 is 19.0 (ksi). This value is much smaller than the result of 137 (ksi) obtained with ADINA. In considering the verification of ADINA as explained in chapter three, it is believed that the results obtained here are correct. The results confirm that the thermal stresses are the predominant stresses.

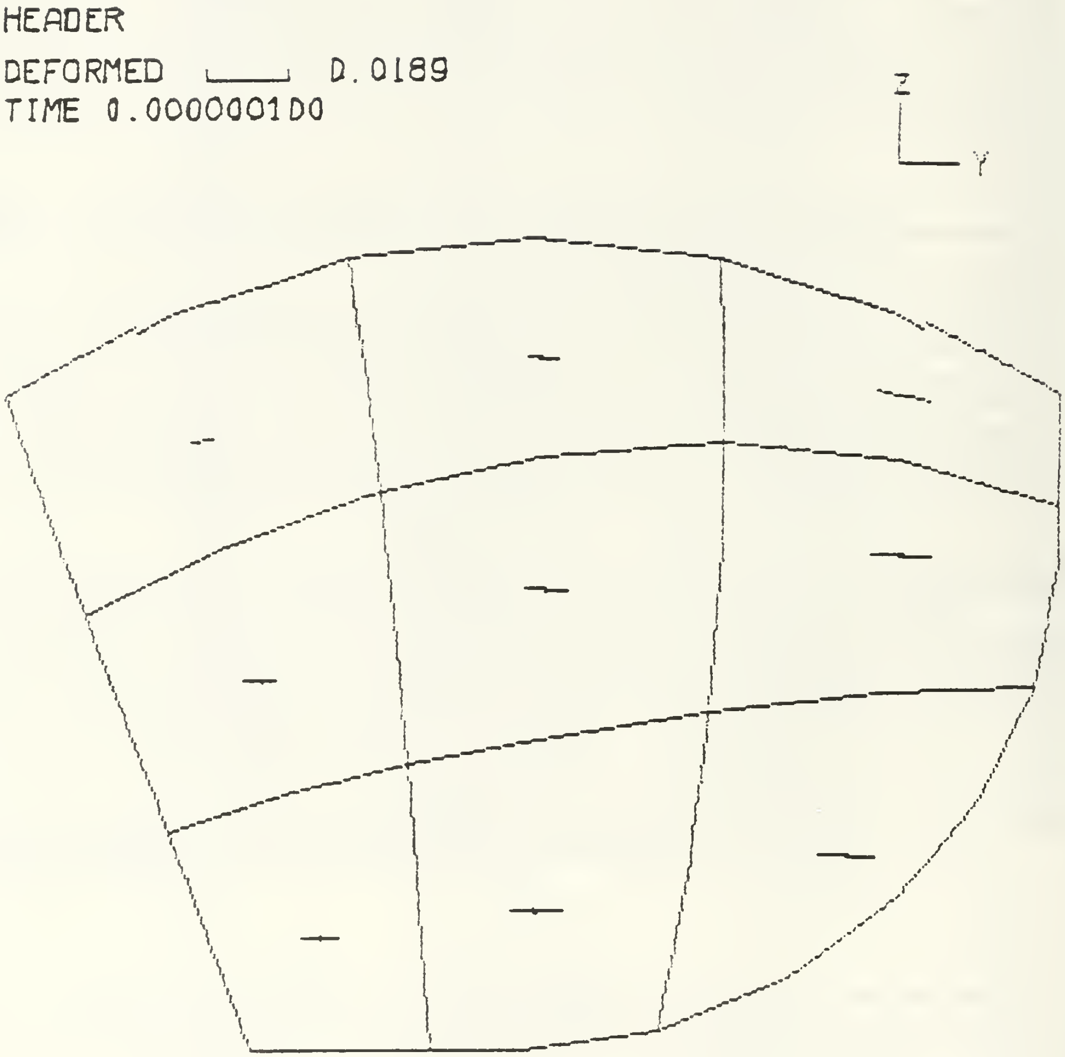


Figure 23. Vector plot of the principal stresses of the coarse mesh for load condition no. 3

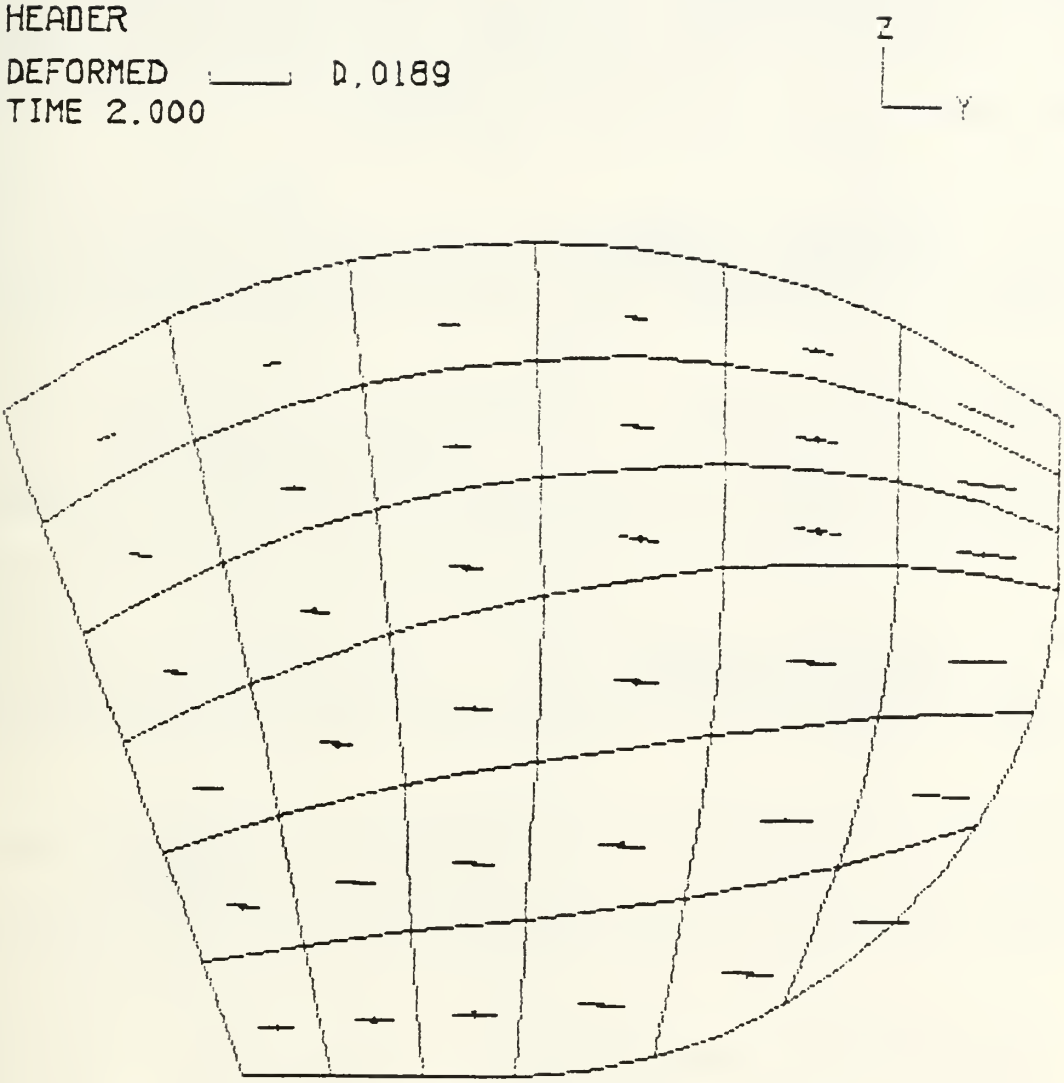


Figure 24. Vector plot of the principal stresses of the fine mesh for load condition no. 3

The accuracy of the results of the problem that has been modeled are very good. There is very little difference between the results of the coarse and fine mesh which means convergence has been achieved. There is no significant difference in the calculated stresses at the boundaries of adjacent elements.

The next step was to use the contact surface option of ADINA for the boundary between the tube and the header. This allows an indication of the coefficient of friction and a determination of its effect on the solution. The maximum stresses are shown in Table 5 and Table 6 for the coarse and fine mesh for a coefficient of friction of zero. These results compare very well with the previous results.

Table 5. MAXIMUM STRESSES FOR THE COARSE MESH, CONTACT SURFACE OPTION

Stresses	Load Condition No. 1	Load Condition No. 2	Load Condition No. 3
σ_{xx} (psi)	-.646923E+03	-.514228E+03	-.135265E+06
σ_{yy} (psi)	-.657614E+03	.362559E+03	-.465231E+05
σ_{zz} (psi)	-.747963E+03	-.112506E+03	-.558613E+04
σ_{yz} (psi)	.134382E+03	.328554E+03	.134376E+05

Table 6. MAXIMUM STRESSES FOR THE FINE MESH, CONTACT SURFACE OPTION

Stresses	Load Condition No. 1	Load Condition No. 2	Load Condition No. 3
σ_{xx} (psi)	-.646745E+03	-.537235E+03	-.137053E+06
σ_{yy} (psi)	-.657250E+03	.495395E+03	-.553930E+05
σ_{zz} (psi)	-.757047E+03	-.139909E+03	-.978366E+04
σ_{yz} (psi)	.139310E+03	.366954E+03	.192709E+05

E. FURTHER MODEL DEVELOPMENT

A detailed study of the problem and the results obtained in the previous section indicated some changes were needed in the model.

It was discovered that the model as developed was not a repeating section. The distance between the center of the tubes is two inches. The right hand side of the model is two inches from the center of the tube. A new model was developed with the right hand side being one inch from the center of the tube. The coarse mesh consists of 43 elements and 211 nodes. The fine mesh has 172 elements and 763 nodes. The models are shown in Figure 25 on page 38 and Figure 26 on page 39.

Figure 19 on page 28 and Figure 22 on page 31 prompted a change in boundary conditions. The deformed shapes showed that the header was not allowed to expand uniformly in the axial direction. The bottom node of the right hand side of the header was fixed and the rest of the nodes on the right hand side were allowed to roll in the z direction. These boundary conditions are shown in Figure 27 on page 40.

The original and deformed shapes for load conditions 1, 2 and 3 for the coarse mesh are shown in Figure 28 on page 41, Figure 29 on page 42 and Figure 30 on page 43. Figure 30 on page 43 shows that the header is now expanding uniformly in the axial direction. The maximum stresses are indicated in Table 7 and Table 8 for the coarse and fine mesh. The ADINA-IN input file for these models is listed in Appendix G.

Table 7. MAXIMUM STRESSES FOR THE COARSE MESH, REPEATING SECTION

Stresses	Load Condition No. 1	Load Conditions 1 and 2	Load Condition No. 3
σ_{xx} (psi)	-.420381E+03	-.566508E+03	-.997953E+05
σ_{yy} (psi)	-.597283E+03	.792176E+03	-.373304E+05
σ_{zz} (psi)	-.825134E+03	-.112852E+04	-.454326E+04
σ_{yz} (psi)	.231712E+03	.838120E+03	.104692E+05

Table 8. MAXIMUM STRESSES FOR THE FINE MESH, REPEATING SECTION

Stresses	Load Condition No. 1	Load Conditions 1 and 2	Load Condition No. 3
σ_{xx} (psi)	-.473741E+03	-.595979E+03	-.101403E+06
σ_{yy} (psi)	-.840852E+03	.130359E+04	-.447373E+05
σ_{zz} (psi)	-.922094E+03	-.126150E+04	-.796674E+04
σ_{yz} (psi)	.313721E+03	.102645E+04	.151684E+05

F. THERMAL GRADIENTS.

The previous change in the model made the thermal gradient in the area of the weld very flat. It was desired to determine what effect different thermal gradients on the right

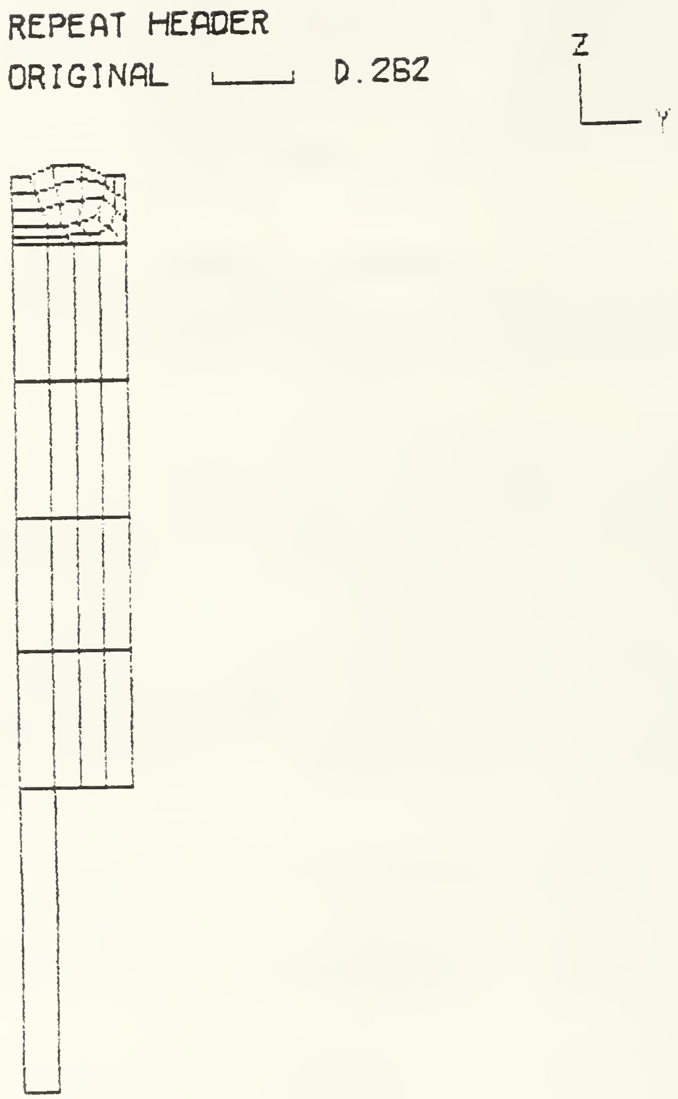


Figure 25. Coarse mesh, repeating section

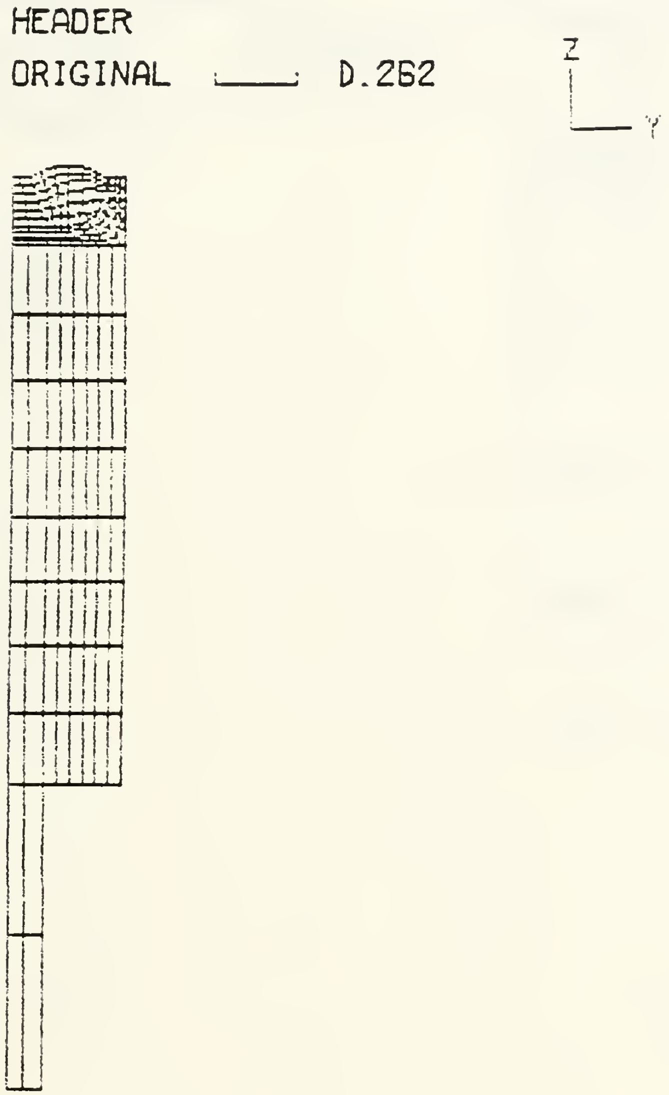


Figure 26. Fine mesh, repeating section

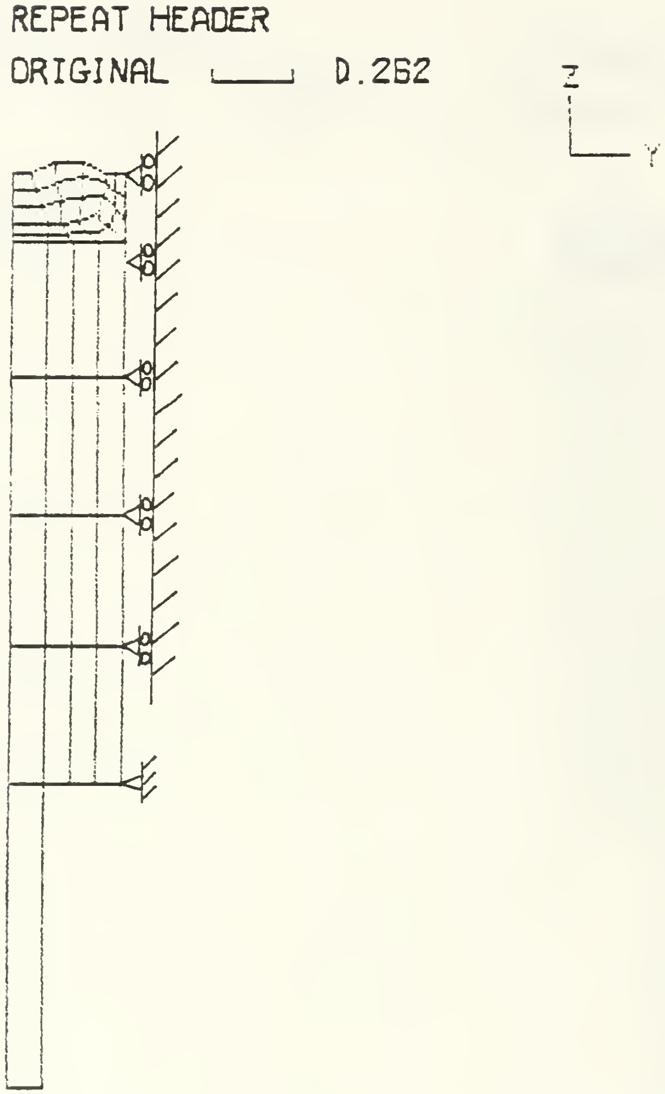


Figure 27. Rolling boundary conditions

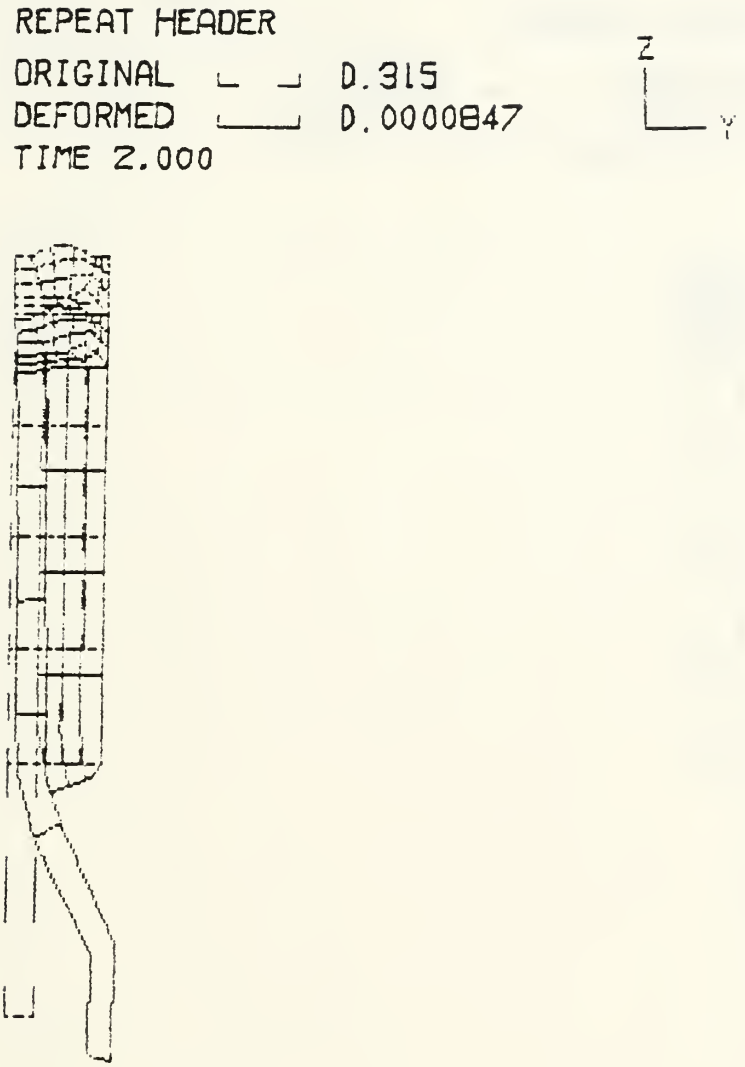


Figure 28. Original and deformed shape of coarse mesh for load condition no.1, repeating section

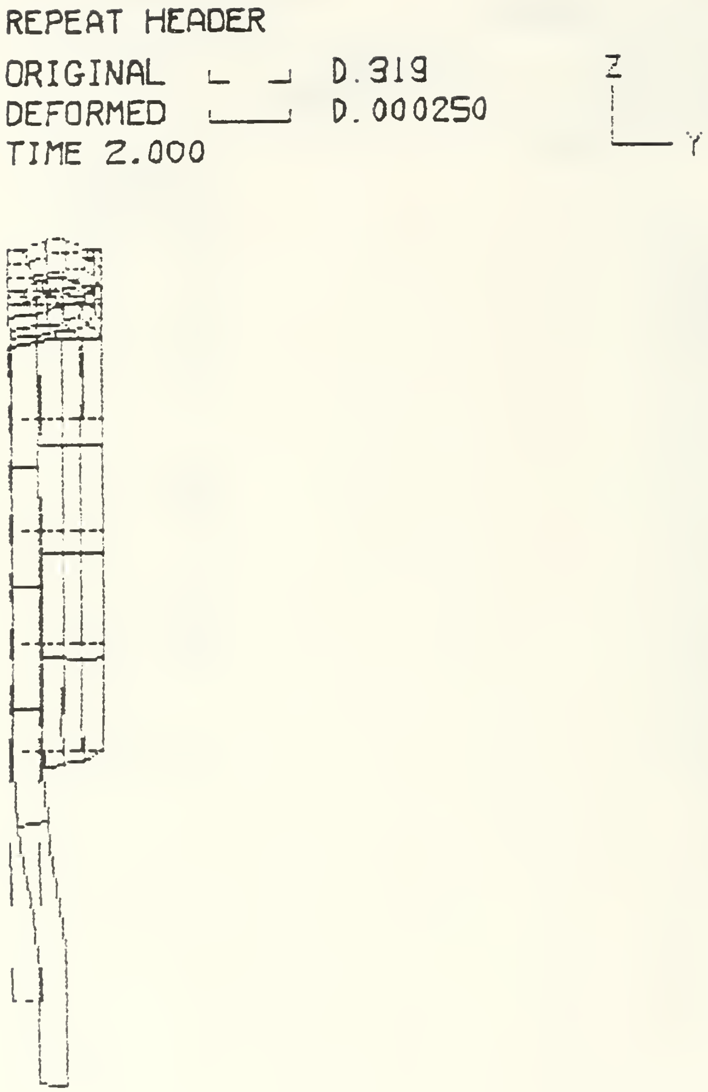


Figure 29. Original and deformed shape of coarse mesh for load condition no. 2 , repeating section

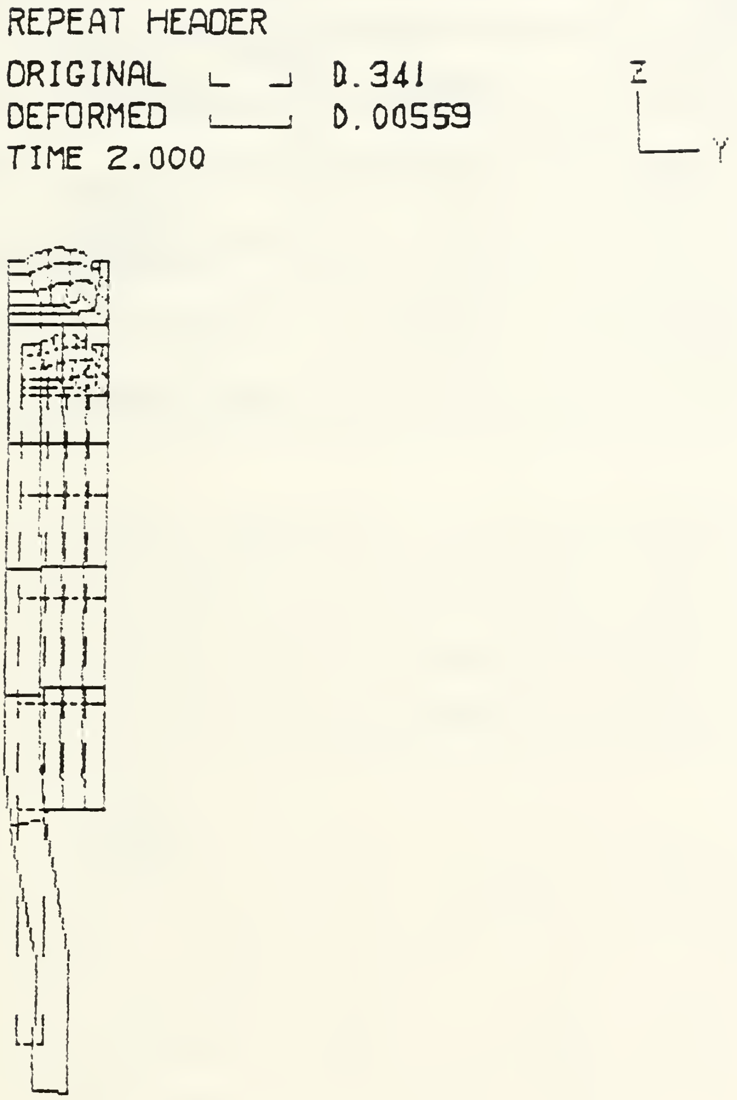


Figure 30. Original and deformed shape of coarse mesh for load condition no. 3 , repeating section

hand side of the model would have on the results. The maximum stresses for a thermal gradient of 100, 10, 2 and 0 degrees F are shown in Table 9.

Table 9. MAXIMUM STRESSES FOR DIFFERENT THERMAL GRADIENTS

Thermal Gradient	σ_{xx} (psi)	σ_{yy} (psi)	σ_{zz} (psi)	σ_{yz} (psi)
100°F	-.997953E+05	-.373304E+05	-.454326E+04	.104692E+05
10°F	-.998908E+05	-.373122E+05	-.454017E+04	.104358E+05
2°F	-.998993E+05	-.373106E+05	-.453990E+04	.104328E+05
0°F	-.999015E+05	-.373102E+05	-.453983E+04	.104321E+05

The results were surprising. The size of the gradient had very little effect on the magnitude of the stresses. The stresses remained very high even for a zero thermal gradient. A study of these results indicated the need for different boundary conditions. Restricting the right hand side of the model to move in the z direction only was not allowing the header to expand outwardly in the radial direction. The header was being forced to expand into the center of the tube which was creating the high stresses in the area of the weld.

The boundary condition chosen is shown in Figure 31 on page 45. The bottom left hand node of the header at the boundary of the tube and the header was fixed. The rest of the bottom nodes of the header were allowed to roll in the y direction. The contact surface option of ADINA could not be used for this solution. The nodes on the boundary were constrained together in the y direction and allowed to move with respect to one another in the z direction, modeling a contact surface with zero coefficient of friction. This was with the exception of the bottom left hand node of the header.

An iterative procedure was then followed to determine the solution of the problem. After each run of the problem, the bottom left hand node of the header was given a permanent displacement to the right equal to the displacement of the corresponding node of the tube at the boundary. This was continued until no overlap occurred. The original and deformed shapes of the final iteration for load condition no. 3 are shown in Figure 32 on page 46. As can be seen, the model is now expanding uniformly in the

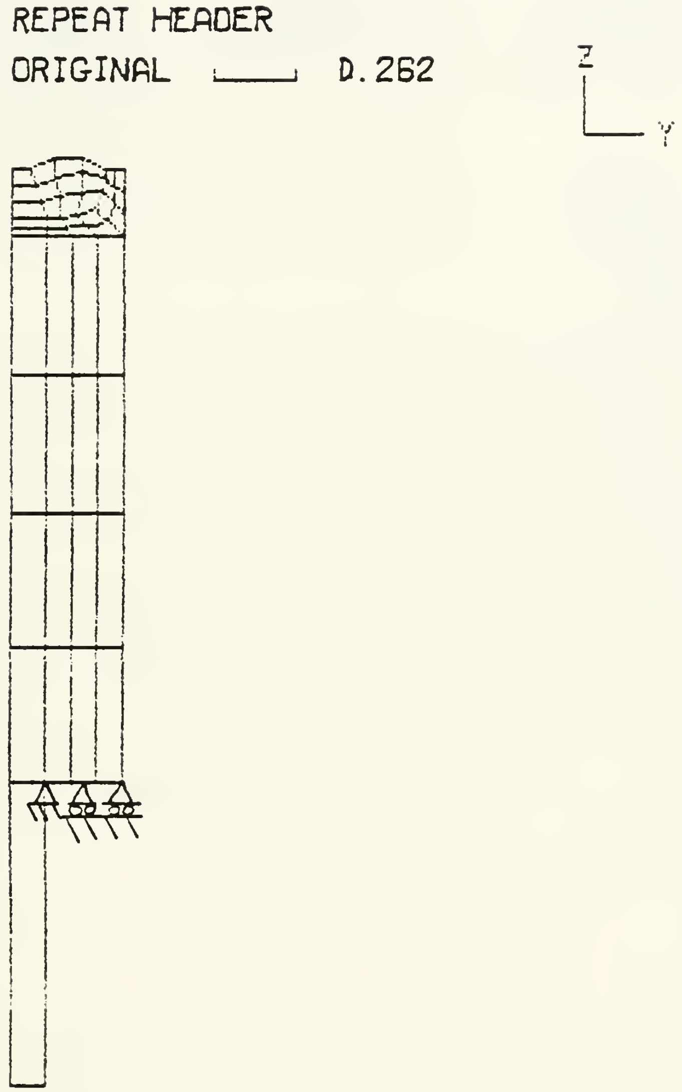


Figure 31. Bottom rolling boundary condition

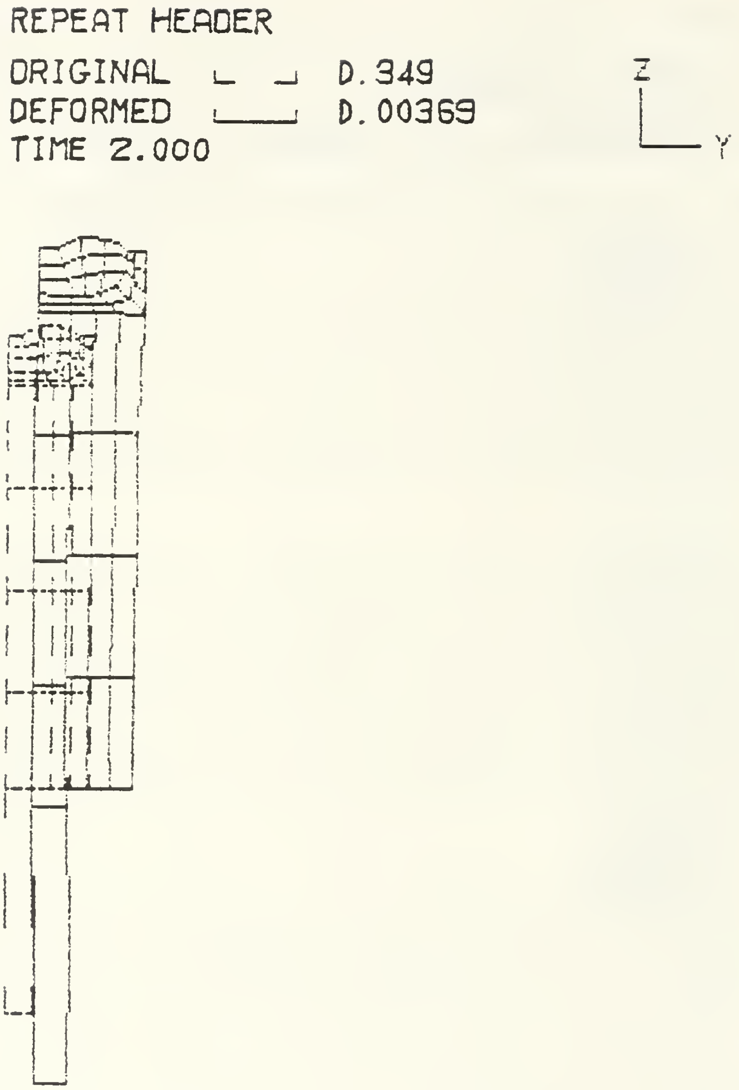


Figure 32. Original and deformed shape of the fine mesh for load condition no. 3, expanding radially and axially

axial direction and outwardly in the radial direction. The maximum stresses in the weld area of the coarse mesh for load condition no. 3 are shown in Table 10.

Table 10. MAXIMUM STRESSES FOR THE COARSE MESH, EXPANDING RADIALLY

Stresses	Load Condition No. 3
σ_{xx} (psi)	.460123E+03
σ_{yy} (psi)	-.932915E+02
σ_{zz} (psi)	.102227E+03
σ_{yz} (psi)	-.584215E+02

These results are much lower than those obtained for the previous model and it is believed that these results are closer to the actual stresses. However, it is also believed that this model is not a true repeating section in that the expansion of the neighboring tubes and the rest of the header will have an effect on this section, probably raising the stresses in the weld area. The need for a 3-dimensional model was indicated.

A 3-dimensional model was also desired in order to apply non-symmetric loading to the model. The major difference between this header and other headers with a similar cross section is that this header is not sectionalized. It has one inlet/outlet header and one intermediate header. This results in a larger temperature gradient from the inlet to the outlet side. A 3-dimensional model would allow this type of non-symmetric loading to be studied.

V. 3-DIMENSIONAL SOLID FINITE ELEMENT MODEL

A. MODEL DEVELOPMENT

The repeating section chosen to be modeled was one tube row. Only half of the row was modeled due to symmetry. The welds were assumed to have the same material properties as the tube and header and no attempt was made to substructure the weld area.

The element chosen to model the structure was the 20-node isoparametric solid element. This element is shown in Figure 33 on page 49.

Figure 34 on page 50 shows the modeling of one tube. Each tube consists of sixty elements. Figure 35 on page 51 shows how the header was connected to the tube. A contact surface was placed between the tube and the header. The entire model is shown in Figure 36 on page 52. Figure 37 on page 53 is another view of the model showing the location of the origin of the axis. The model consists of 288 elements and 1957 nodes. Figure 38 on page 54, Figure 39 on page 55 and Figure 40 on page 56 show a view of the model looking from the x, y and z directions.

The hidden line computer code developed by David R. Hedgley, Jr. of the Ames Research Center was utilized to check the model. Different views are shown in Figure 41 on page 57 and Figure 42 on page 58.

The following boundary conditions were imposed. Every node in the $y=0$ plane was constrained to roll in that plane. In addition the node at the origin was fixed and the nodes above the origin along the positive x axis were constrained to roll only in the x direction.

B. INTERNAL PRESSURE LOAD

The internal pressure load of 700 psi was applied to the inside nodes of the tube and header. It was then discovered that ADINA does not optimize the band-width of contact surfaces. The bandwidth of this model is approximately 2700 and the problem was too large to be solved on the VAX/VMS operating system. The ADINA-IN input file for the contact surfaces is listed in Appendix H for reference.

A contact surface was then modeled by constraining the corresponding nodes of the tube and header to move together in the y and z direction, but allowing them to move relative to one another in the x direction. This assumes a coefficient of friction of zero and reduced the bandwidth to approximately 1000.

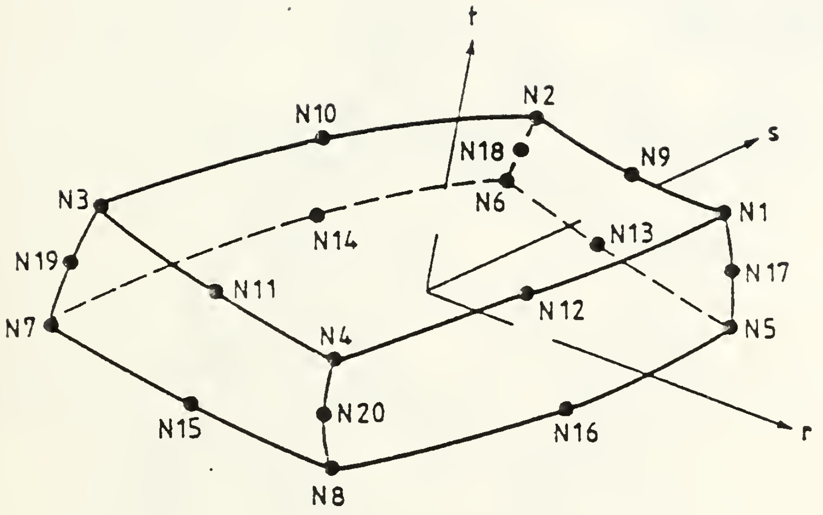


Figure 33. 20-node isoparametric solid element

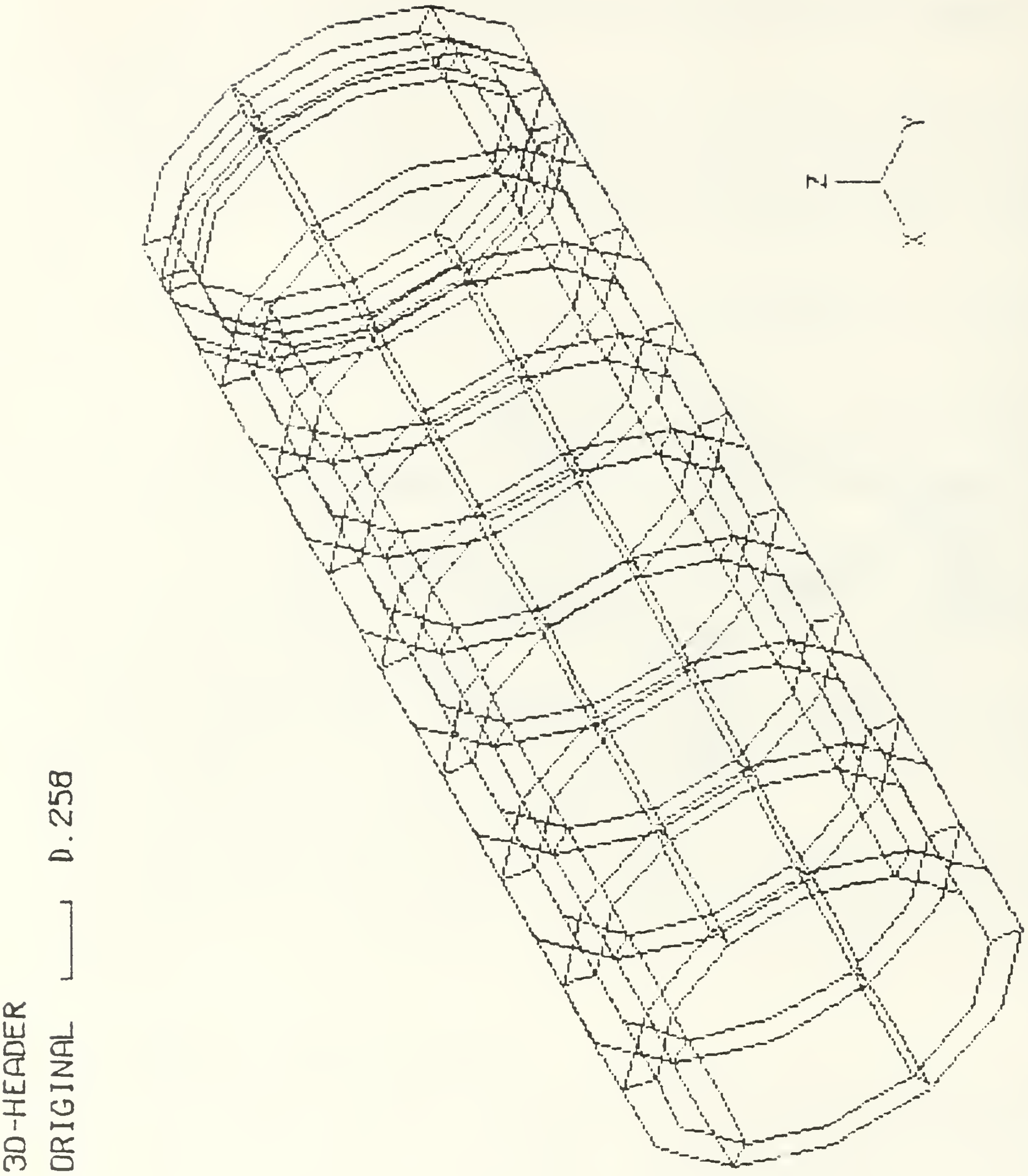


Figure 34. Mesh for one tube

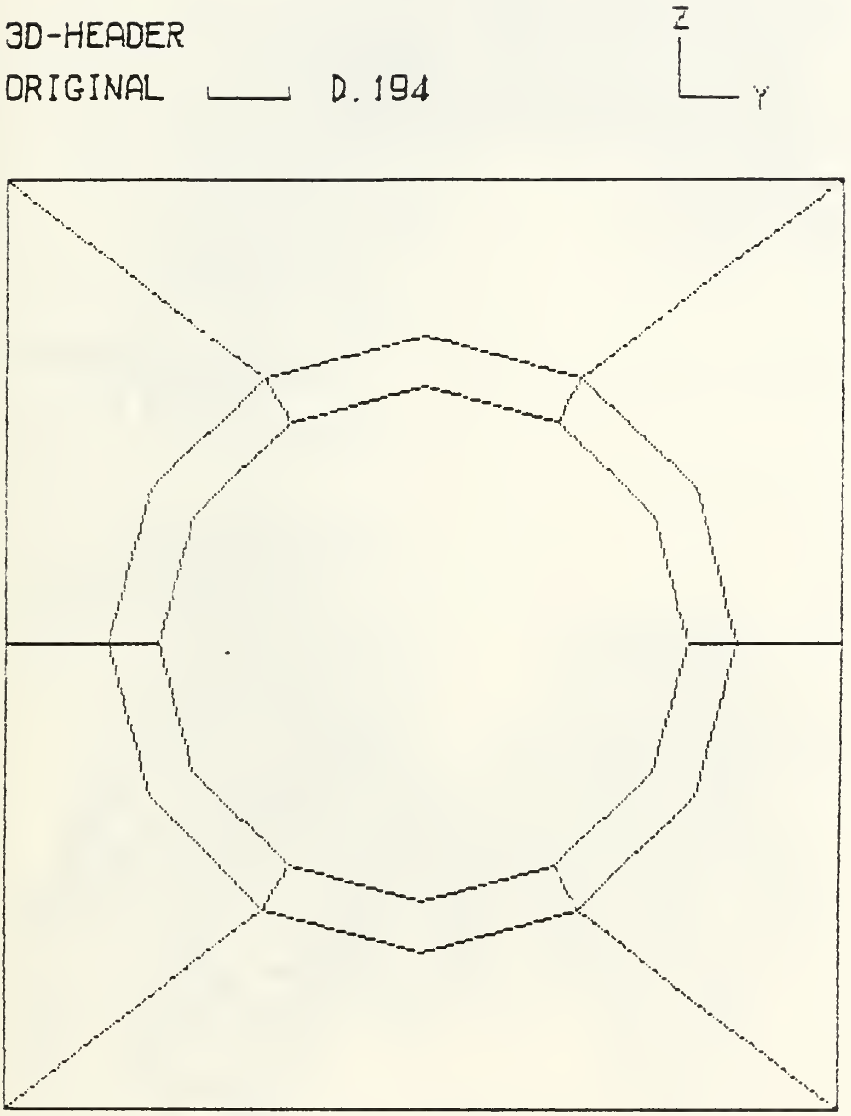


Figure 35. Attachment of header to a tube

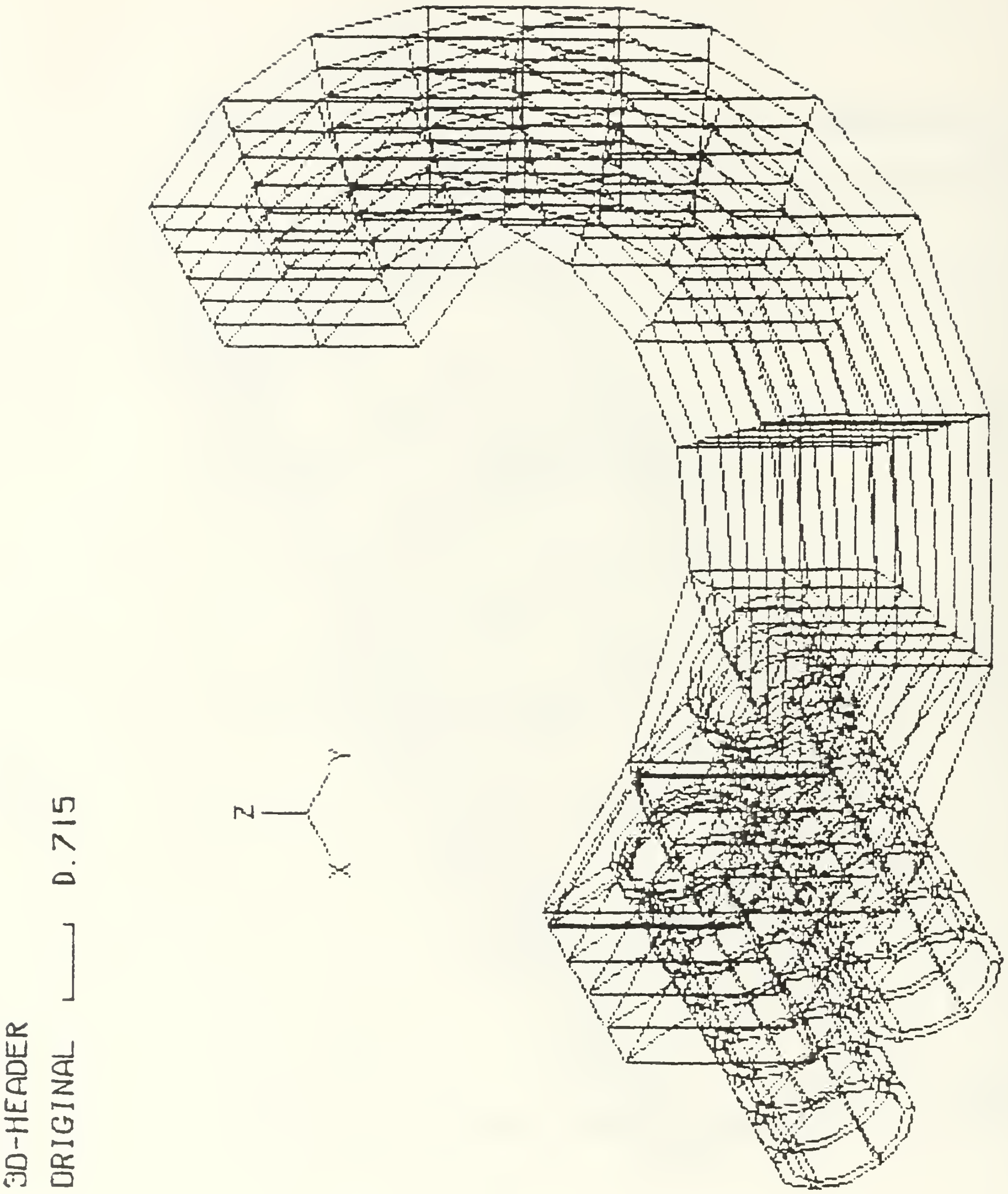


Figure 36. 3-dimensional model

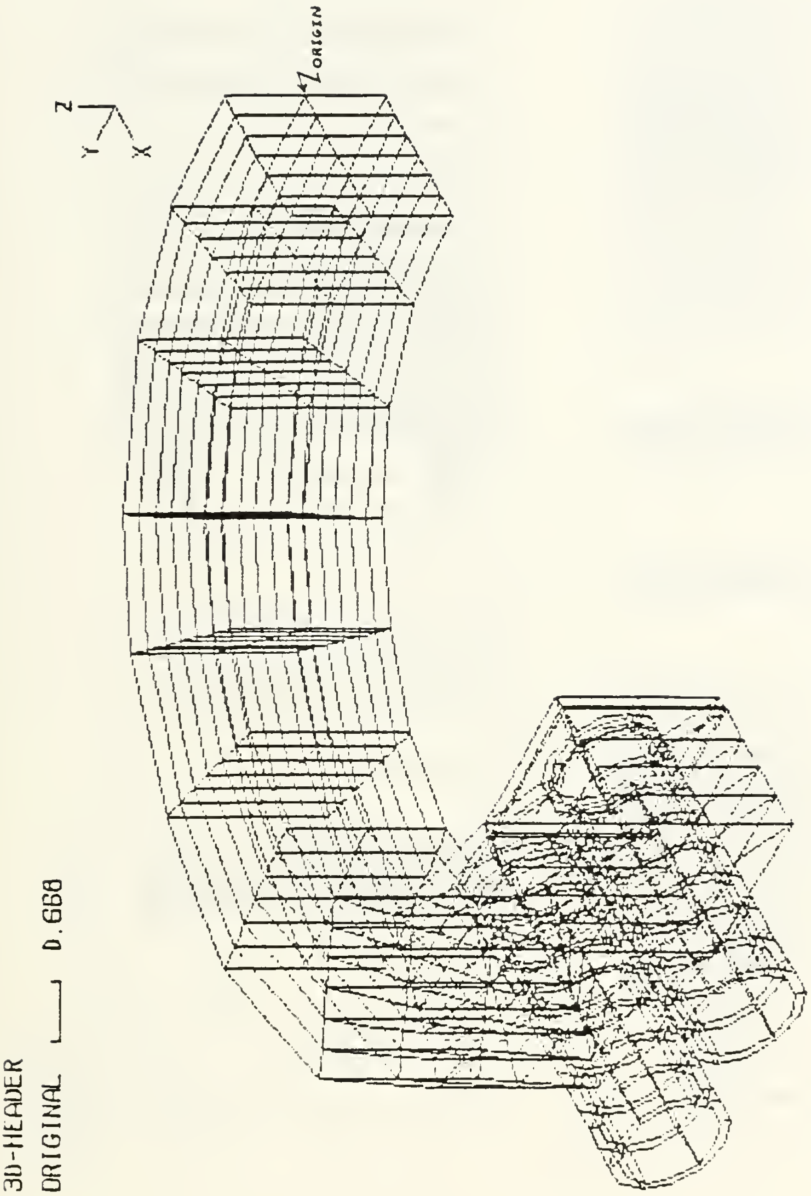


Figure 37. 3-dimensional model showing the location of the origin

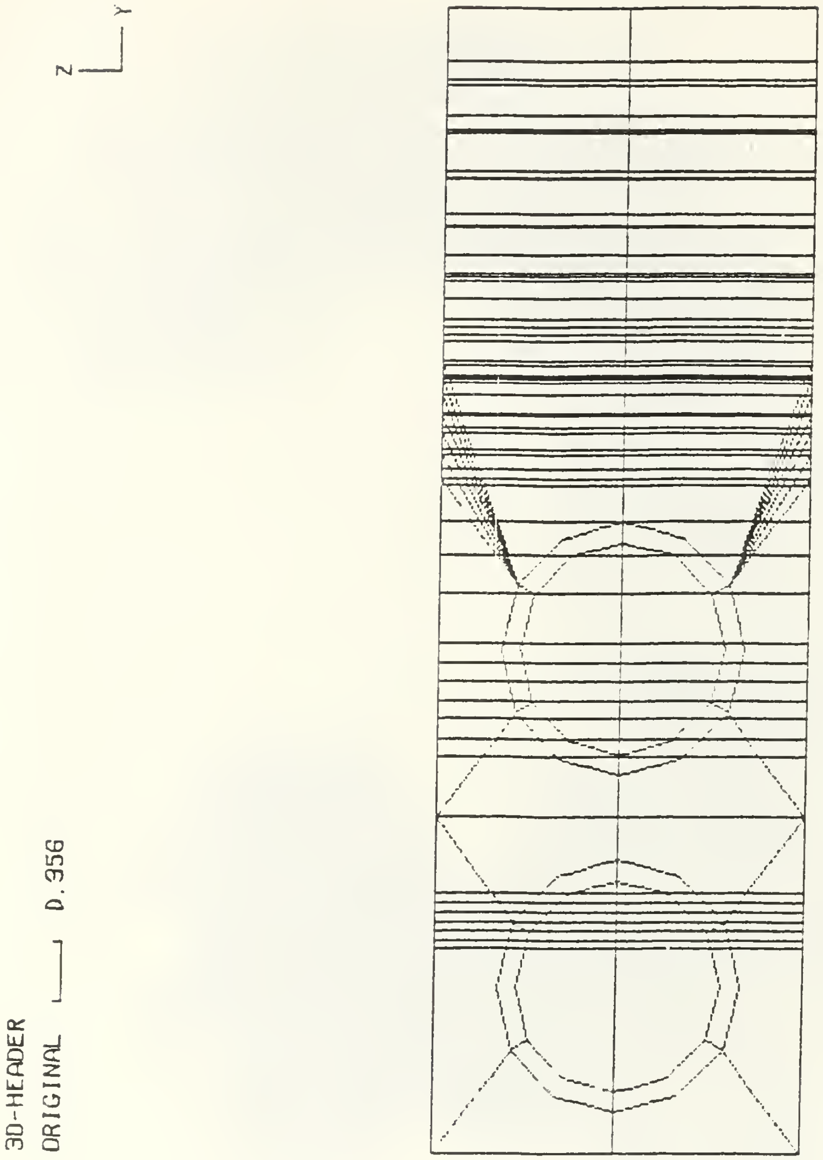


Figure 38. View of 3-dimensional model from the x direction

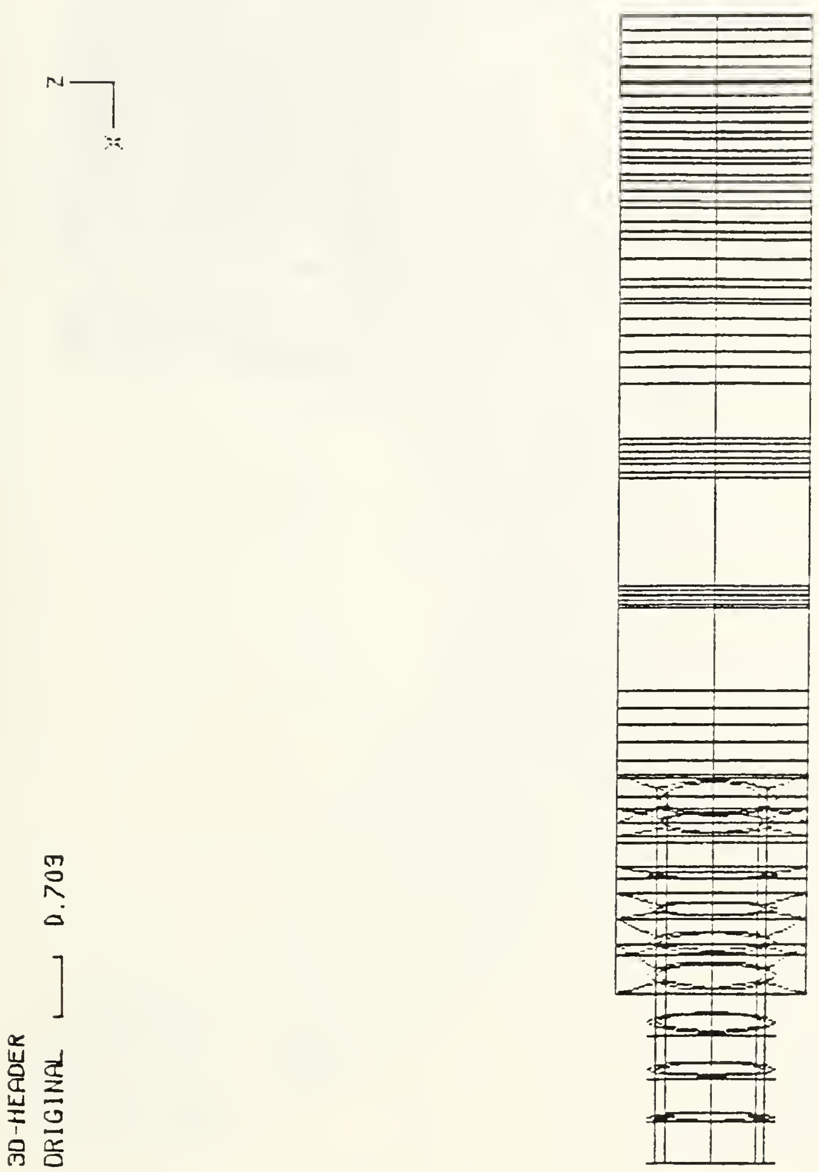


Figure 39. View of 3-dimensional model from the y direction

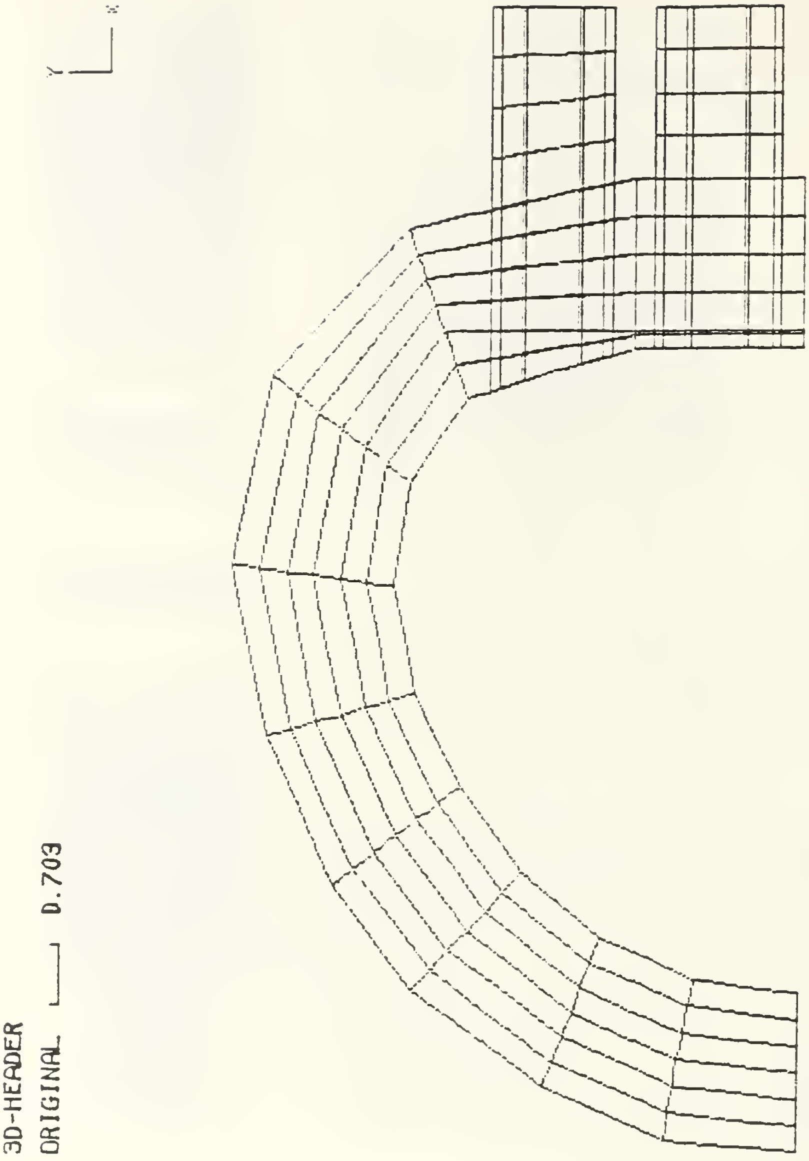


Figure 40. View of 3-dimensional model from the z direction

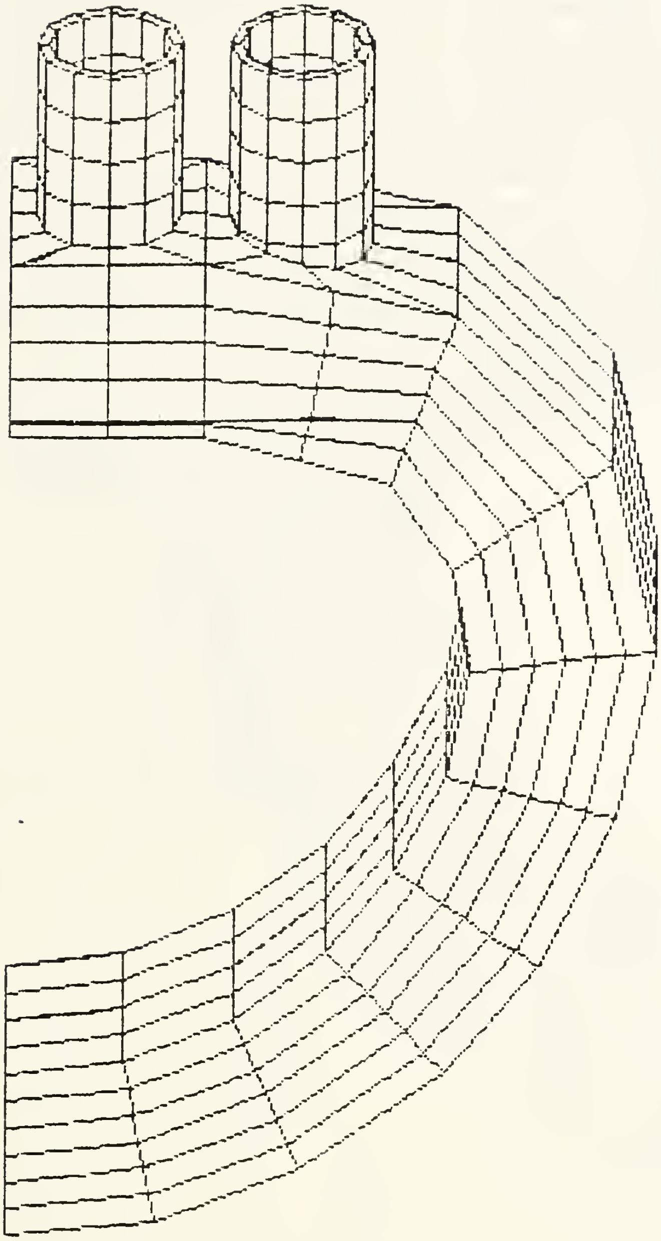


Figure 41. View of model using hidden line removal

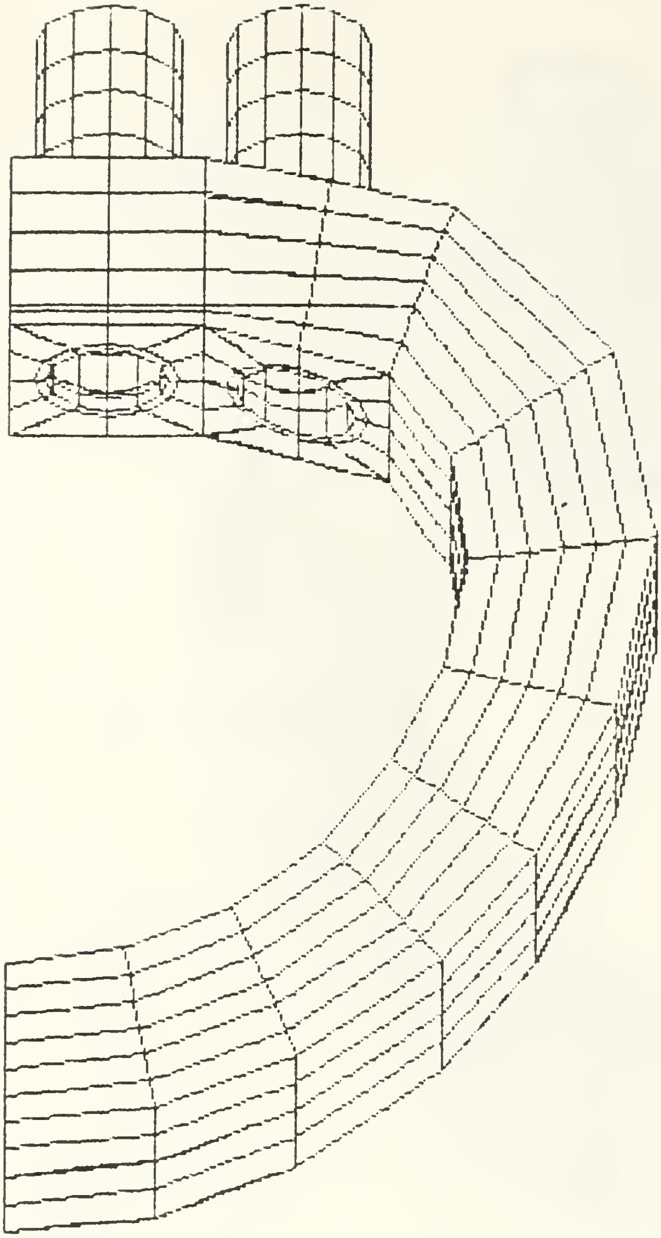


Figure 42. Another view of the model using hidden line removal

It then became necessary to enforce symmetry on either side of the $z=0$ plane. Every node in this plane was constrained to roll in the plane. It is understood that this enforced symmetry is more costly than modeling only half of the structure. The entire section was modeled to allow a study of unsymmetric temperature loading. The ADINA-IN input file is listed in Appendix I.

Figure 43 on page 60 shows the original and deformed shapes for this loading condition. Table 11 lists the maximum stresses in the area of the weld.

Table 11. MAXIMUM STRESSES 3-DIMENSIONAL MODEL

Stresses	Internal pressure load
σ_{xx} (psi)	-.984072E+03
σ_{yy} (psi)	-.111941E+04
σ_{zz} (psi)	.184639E+04
σ_{xy} (psi)	-.487366E+03
σ_{xz} (psi)	.235319E+03
σ_{yz} (psi)	-.814224E+03

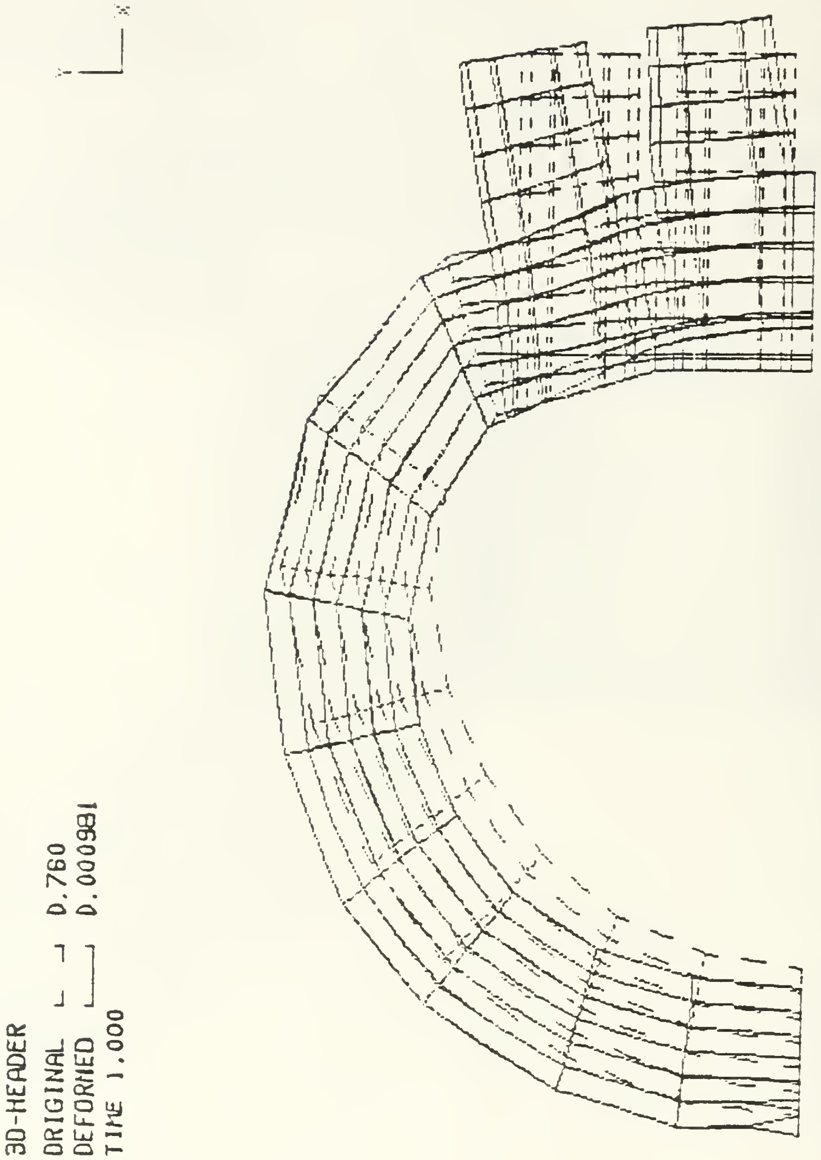


Figure 43. Original and deformed shape of the 3-dimensional model, internal pressure load

VI. CONCLUSIONS

A. DISCUSSION OF RESULTS

The maximum stresses obtained for the axisymmetric model were between 137 (ksi) and .46 (ksi), dependent upon the boundary conditions imposed. The axisymmetric model does not adequately represent the physical boundary conditions and the actual stress is somewhere between these two figures.

A 3-dimensional model has been developed which allows an accurate representation of the boundary conditions. The maximum stress for the internal pressure load in the area of the weld was 1.85 (ksi). This model also allows non-symmetric loading to be applied.

B. OPPORTUNITIES FOR FURTHER RESEARCH

The next step in solving this problem is to obtain results for the thermal loading. The initial loading should be static but the transient loading should also be studied. In studying the transient problem, a consideration should be made of the temperature dependence of the material properties of the structure. Another area for research would be the consideration of creep.

The major attempt of this report was to develop a 3-dimensional model which could be used to investigate the failures that have occurred in the superheater header attachment welds. This model can also be used to investigate any needed design changes. It is hoped that this model will be used for further investigation of this problem.

APPENDIX A. ADINA-IN PROCEDURES

These procedures are for the VAX/VMS operating system utilizing the plot-10 graphics library.

To operate ADINA-IN in the batch mode, a data file which defines the problem must be created. Assign this data file to a logical unit number and run ADINA-IN.

Now create the database. All of the input to ADINA-IN is stored on this database. The Command is DATAB CREATE. Next read the data file by using the command: READ (logical unit number).

The model can now be plotted using the frame, mesh and plot commands as explained in [Ref. 2: pp. 5.25-1 to 5.25-20]. The CONTROL command must be set to the correct parameters to use graphics. For the VAX/VMS operating system utilizing the plot-10 graphics library, set baudrate=4800, system=2, device=2 and option=1024. Changes can be made to the model by exiting and changing the data file or by typing in changes interactively. All changes will be saved on the database.

When the problem is properly defined, create the ADINA input file using the command ADINA. Exit ADINA-IN by typing in END.

ADINA-IN will have created two files. FOR001.DAT is the database. This database can best be saved by renaming it to a unique file name. To make changes assign the database to logical unit FOR001 and run ADINA-IN. Use the command DATABASE OPEN and then make any necessary changes.

The second file created by ADINA-IN is FOR002.DAT and this is the input file for ADINA. This file should be renamed to a unique filename and assigned to logical unit number FOR005. Assign an output file to logical unit number FOR006. Ensure there are no FOR*.* files in the directory as this can interfere with the operation of ADINA. Now run ADINA. The requested results will be printed in the assigned output file.

APPENDIX B. ADINA-IN PROCEDURES FOR THE THERMAL STRESS PROBLEM

ADINA-IN is also used for creating the input file for ADINAT. This particular version of ADINA-IN will not create the entire file which necessitates some minor editing of the ADINAT input file before ADINAT can be run.

The temperature loading in this thesis was done by using the LOADS TEMPERATURE command in the ADINA-IN input file. After the problem is defined in ADINA-IN, use the ADINAT command to generate the ADINAT input file.

ADINA-IN again creates two files. FOR001.DAT is the database and FOR002.DAT is the ADINAT input file. Rename these files.

The ADINAT input file must now be edited. Search for the line which has the letters 'KKKKKK'. This line must be deleted and the specific heat entered. The line just above this line must also be deleted and the thermal conductivity entered. Exit the ADINAT input file.

Assign the ADINAT input file to logical unit number FOR005 and assign an output file to logical unit number FOR006. Run ADINAT. ADINAT creates several files, most of which are used for the operation of the code. The final nodal point temperatures and heat fluxes are printed in the output file. The nodal temperatures are also stored in FOR056.DAT. This file must be renamed to a unique filename.

ADINA-IN must now be run again to create the input file for ADINA to solve for the thermal stresses. Assign the nodal temperature file to logical unit number FOR056.

The ADINA-IN input file must be changed. Delete the LOADS TEMPERATURE command and indicate on the MASTER command line that ITP56 = 1. Run ADINA-IN and read the changed input file. Ensure all FOR*.* files are deleted before doing this. Then use the ADINA command to create the ADINA input file. ADINA can now be run as explained in the last paragraph of Appendix A.

APPENDIX C. ADINA-PLOT PROCEDURES

ADINA created several files besides the assigned output file. Most of these files are used for the operation of the code. File FOR060.DAT is the porthole file for ADINA-PLOT.

Before running ADINA-PLOT, ensure all FOR001.DAT files are deleted and that logical unit number FOR001 is deassigned. Run ADINA-PLOT. First create the database using the DATABASE CREATE command. All of the information in the porthole file is now loaded.

Ensure the control information is correct. The model can now be plotted and the results listed as explained in [Ref. 6].

Exit ADINA-PLOT with the command END. ADINA-PLOT will have created a database with filename FOR001.DAT. Rename this file. To look at the results again, assign the database to logical unit number FOR001 and use the DATABASE OPEN command when running ADINA-PLOT.

APPENDIX D. VERIFICATION OF ADINA - CANTILEVER BEAM PROBLEM

The cantilever beam problem modeled is shown in Figure 44 on page 66. A moment of 360 k-in is applied to the end of a cantilever beam which is 48 inches long and 12 inches wide.

The classical equations as listed in [Ref. 7: pp. 215 and 737] are:

$$\sigma = My/I \qquad (A.1)$$

$$\delta_b = M_0L^2/2EI \qquad (A.2)$$

The finite element model showing both the original and deformed shapes is shown in Figure 45 on page 67. A nine node plane stress element was used. Table 12 shows a comparison of the results for several nodes. As can be seen, ADINA yields exact results for this problem. The following is the ADINA-IN input file:

Table 12. COMPARISON OF RESULTS

Comparison	Beam Theory	ADINA
displacement of node 10 (inch)	.096	.096
stress at node 1 (psi)	15	15
stress at node 12 (psi)	-15	-15

```
DATAB CREATE
HEAD ' CANTILEVER BEAM'
*
MASTER REACTIONS=YES IDOF=100111
PRINTOUT MAX
ANALYSIS TYPE=STATIC
*
COORDINATES / ENTRIES NODE X  Y  Z
                      1    0  0  0
                      5    0  48 0
                      15   0  48 12
                      11   0  0  12

*
```

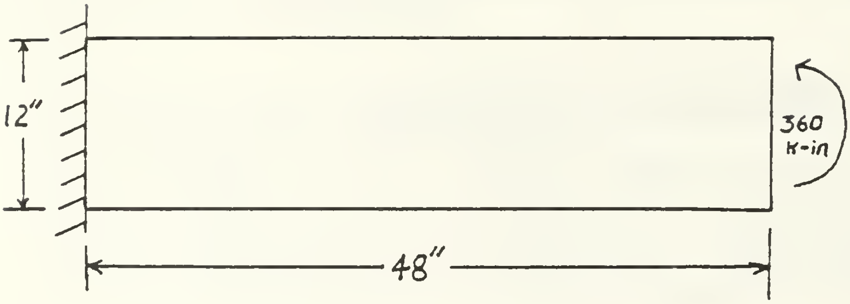


Figure 44. Cantilever beam with concentrated moment

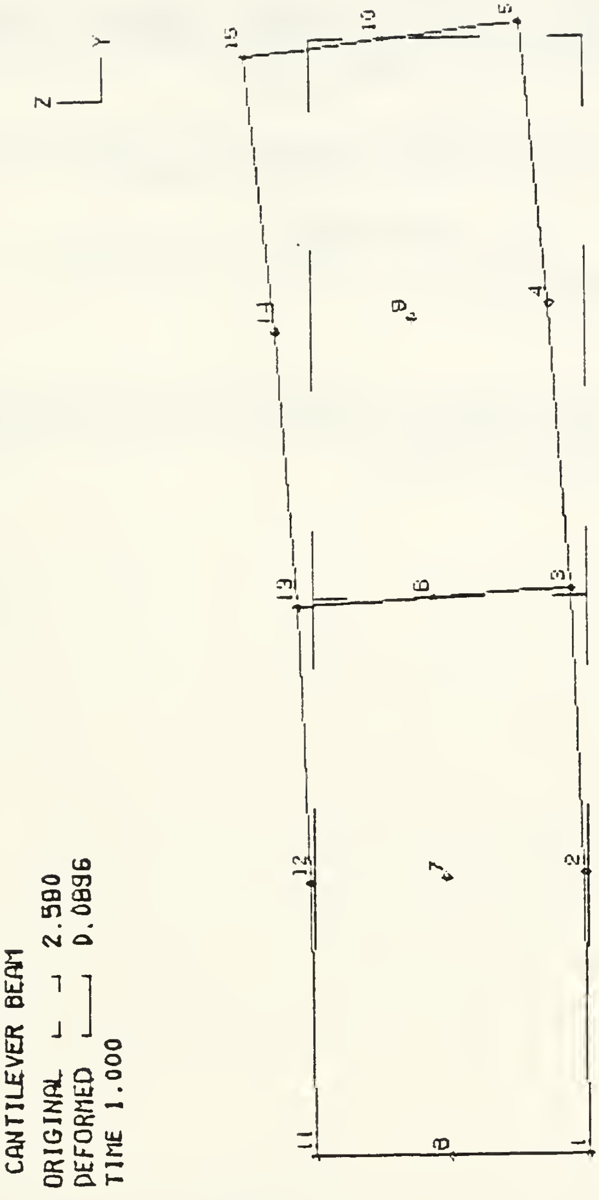


Figure 45. Original and deformed shapes for the cantilever beam

```
MATERIAL 1 ELASTIC E=3E4 NU=0.0 D=1
*
EGROUP 1 PLANE SUBTYPE=STRESS2 RESULTS=STRESSES INT=6
STRESSTABLE N=1 P1=1 P2=2 P3=3 P4=4 P5=5 P6=6 P7=7 P8=8 P9=9
EDATA / ENTRIES EL THICK
                1  1
                2  1
GSURFACE 1 5 15 11 EL1=2 EL2=1 NODES=9
*
BOUNDARIES 111111 TYPE=NODES / 1 6 11
*
LOADS CONCENTRATED
5 2 30
15 2 -30
*
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=W PLOTS=N
```

APPENDIX E. VERIFICATION OF ADINA - ANNULAR DISK PROBLEM

The classical equations for the thermal stresses are listed in [Ref. 8 : p. 259]:

$$\sigma_r = \alpha E[-1/r^2 \int_a^r Trdr + (r^2 - a^2)/r^2(b^2 - a^2) \int_a^b Trdr] \tag{E.1}$$

$$\sigma_\theta = \alpha E[-T + 1/r^2 \int_a^r Trdr + (r^2 + a^2)/r^2(b^2 - a^2) \int_a^b Trdr] \tag{E.2}$$

where:

- a = inner radius, .63 inch
- b = outer radius, 3.0 inch
- T = temperature distribution, 399.569212 - 86.3436r + 12.16239867r^2
- E = 29600000 psi
- α = .0000065 in/in/°F

The finite element model showing the original and deformed shapes is shown in Figure 46 on page 70. A nine node plane axisymmetric element was used. Table 13 shows a comparison of the results. The comparison is very good. Most of the difference can be attributed to the fact that the results for the disk theory were computed at the nodes where as the results for ADINA are calculated at the Gaussian integration points. The following is the ADINA-IN input file:

Table 13. COMPARISON OF RESULTS

r (inch)	Stresses from Disk Theory (psi)	Stresses from ADINA (psi)
.63	σ_θ = -.139E+05	σ_θ = -.120961E+05
1.815	σ_r = -.2577E+04	σ_r = -.253146E+04
1.815	σ_θ = .1715E+04	σ_θ = .169057E+04
3.0	σ_θ = .534E+04	σ_θ = .511644E+04

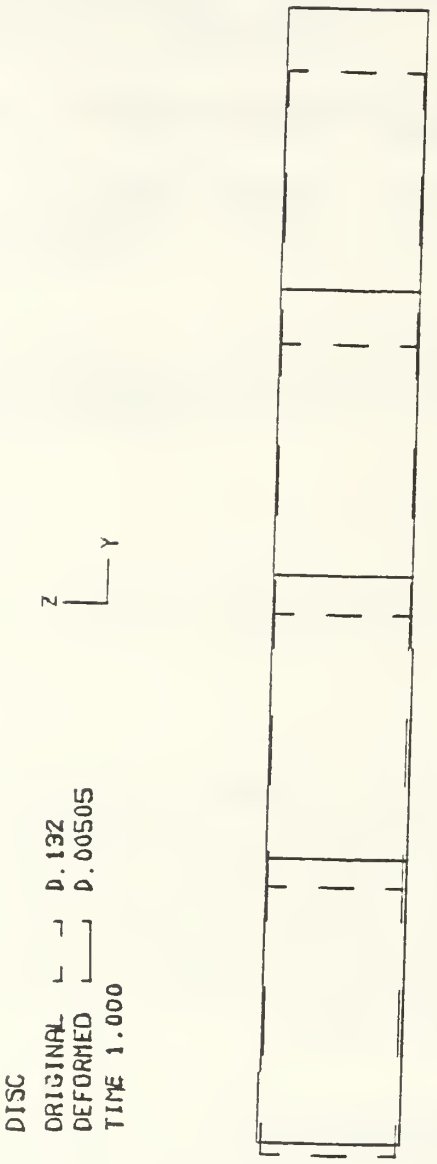


Figure 46. Original and deformed shapes for the disk

```
DATAB CREATE
HEAD 'DISC'
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=WAIT PLOTS=NO
*
COORDINATES / ENTRIES NODE X    Y    Z
                      1    0    .63  0
                      2    0    .63  .3
                      3    0    3.0  0
                      4    0    3.0  .3
*
MATERIAL 1 THERMO-ELASTIC
-2000  29600000  .3  .0000065
 2000  29600000  .3  .0000065
*
EGROUP 1 PLANE SU=AXISYMM
GSURFACE 4 2 1 3 EL1=4 EL2=1 NO=9
*
MASTER REACTIONS=YES IDOF=100111
PRINTOUT MAX
ANALYSIS TYPE=STATIC
*
BOUNDARIES 101111 TYPE =NODES/12 STEP 1 TO 20
*
LOADS TEMP TR=0
1  350
2  350
20 350
3  250
4  250
12 250
*
```

APPENDIX F. VERIFICATION OF ADINA - CHIMNEY PROBLEM

The chimney problem modeled is shown in Figure 47 on page 73. The inside surface is at a uniform temperature of 650 degrees C and the outside surface is at a temperature of 150 degrees C.

The finite element model is shown in Figure 48 on page 74. A nine node plane stress element was used.

A finite difference temperature distribution of this problem was obtained from Professor G. Cantin of the Naval Postgraduate School. The results had converged to the exact solution. Table 14 shows a comparison of the results for several nodes. The comparison is very good. The following is the ADINA-IN input file:

Table 14. RESULTS FOR CHIMNEY PROBLEM

Node	Temperatures from Finite Difference (°C)	Temperatures form ADINA (°C)
10	3.6933026E+02	3.68497E+02
12	3.4661577E+02	3.39891E+02
15	2.5149076E+02	2.52863E+02
16	3.4891941E+02	3.42042E+02
17	3.8732346E+02	4.01579E+02

```
DATAB CREATE
HEAD 'CHIMNEY'
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=WAIT PLOTS=NO
*
COORDINATES/ENTRIES NODE X  Y    Z
                     1   0  2.0  1.5
                     2   0  1.0  1.5
                     3   0  1.0  1.0
                     4   0  2.0  1.0
                     5   0  0    1.0
                     6   0  0    0
                     7   0  2.0  0
*
MATERIAL 1 THERMO-ELASTIC
  -2000 29600 .3 .0000065
   2000 29600 .3 .0000065
*
```

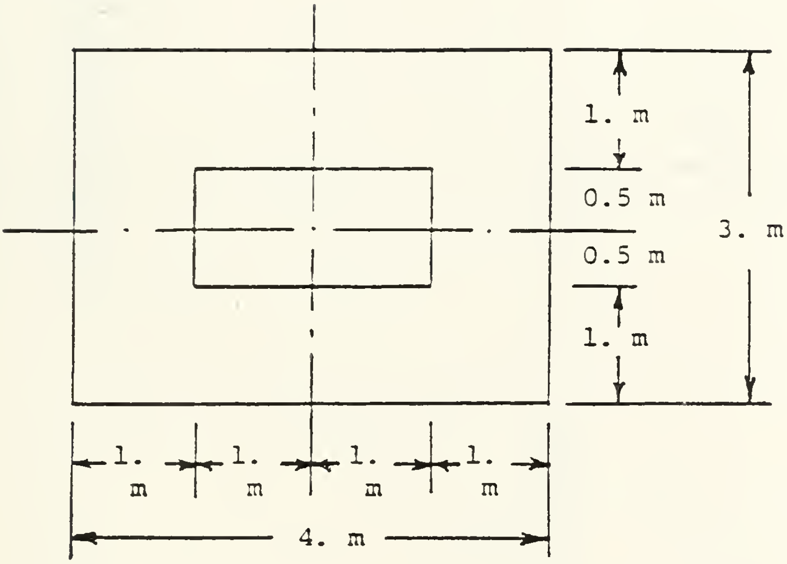


Figure 47. Chimney problem

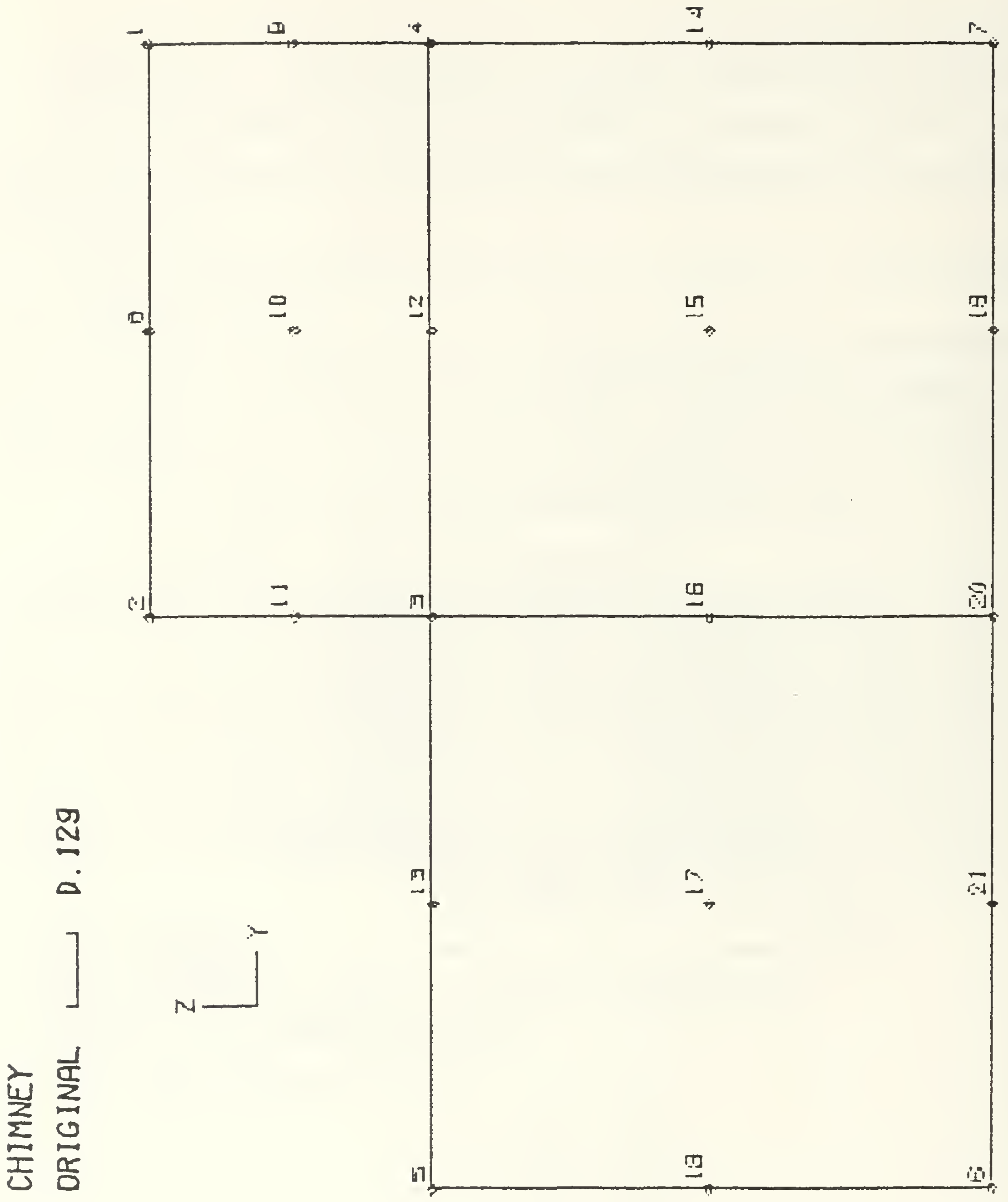


Figure 48. Finite element model of the chimney

```
EGROUP 1 PLANE SU=STRESS2
EDATA
1 1
2 1
3 1
GSURFACE 1 2 3 4 EL1=1 EL2=1 NO=9
GSURFACE 4 5 6 7 EL1=2 EL2=1 NO=9
*
MASTER REACTIONS=YES IDOF=100111
PRINTOUT MAX
ANALYSIS TYPE=STATIC
*
LOADS TEMPERATURE
 1   150
 9   150
 4   150
14   150
 7   150
19   150
20   150
21   150
 2   650
11   650
 3   650
13   650
 5   650
*
```

APPENDIX G. ADINA-IN INPUT FILE FOR THE AXISYMMETRIC PROBLEM

```
DATAB CREATE
*INPUT FOR THE COARSE MESH, 2-DIMENSIONAL AXISYMMETRIC MODEL
HEAD 'REPEAT HEADER'
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=WAIT PLOTS=NO
*COORDINATES ARE DEFINED
COORDINATES / ENTRIES NODE   X    Y           Z
                      1      0    .63         3.0
                      3      0    .693        3.0
                      37     0    .63         2.844
                      39     0    .75         2.844
                      60     0    .63         2.782
                      61     0    .75         2.782
                      70     0    .63         1.0
                      71     0    .75         1.0
                      72     0    .75001      1.0
                      85     0    .63         0.0
                      87     0    .75         0.0
                      100    0    .938        3.0
                      200    0    .82         2.837
                      152    0    .938        2.97333333
                      204    0    .9322366    2.93059481
                      211    0    .901        2.88
                      210    0    .84513864   2.84814711
                      207    0    .792        2.844
                      209    0    .813        2.969
                      126    0    .938        2.98666666
                      178    0    .938        2.96
                      208    0    .813        2.844
                      206    0    .771        2.844
                      50     0    1.0         3.0
                      6      0    1.0         2.782
                      75     0    1.0         1.0
*MATERIAL PROPERTIES ARE DEFINED
MATERIAL 1 THERMO-ELASTIC
-2000  29600000  .3 .0000065
 2000  29600000  .3 .0000065
*THE ELEMENT IS DEFINED
EGROUP 1 PLANE SU=AXISYMM
*THE MESH FOR THE TUBE IS GENERATED
GSURFACE 3 1 37 39 EL1=1 EL2=3 NO=9 NC=B
GSURFACE 39 37 60 61 EL1=1 EL2=2 NO=9 NC=B
GSURFACE 61 60 70 71 EL1=1 EL2=4 NO=9 NC=B
GSURFACE 71 70 85 87 EL1=1 EL2=1 NO=9 NC=B
*NODES FOR THE WELD ARE GENERATED
LINE A 3 100 NCENTER=200 EL=3 M=1
LINE N 100 204 126 152 178
LINE A 204 211 NCENTER=209 EL=1 M=1
LINE C 100 211 204
LINE A 211 210 NCENTER=209 EL=1 M=1
LINE N 210 39 208 207 206
LINE C 211 39 210
*THE MESH FOR THE WELD IS GENERATED
GSURFACE 100 3 39 211 EL1=3 EL2=3 NO=9 NC=B
*NODES FOR THE HEADER ARE GENERATED
LINE C 100 39 204 211 210
LINE S 50 6 EL=3 M=1
LINE S 6 61 EL=3 M=1
LINE C 50 61 6
*THE MESH FOR THE HEADER IS GENERATED
```

```
GSURFACE 50 100 39 61 EL1=2 EL2=6 NO=9 NC=B
GSURFACE 6 61 72 75 EL1=3 EL2=4 NO=9 NC=N
*PORTIONS OF THE MODEL ARE DEFINED FOR PLOTTING
EZONE TUBE01
1 STEP 1 TO 3
EZONE TUBE02
4 STEP 1 TO 10
EZONE WELD
11 STEP 1 TO 19
EZONE HEAD
20 STEP 1 TO 43
BZONE CLOSE XMIN=0 XMAX=0 YMIN=.63 YMAX=1.0 ZMIN=2.782 ZMAX=3.1
*THE MASTER DEGREES OF FREEDOM ARE DEFINED
MASTER REACTIONS=YES IDOF=100111 DT=1 NSTEP=2 ITP56=1
PRINTOUT MAX
ANALYSIS TYPE=STATIC
*THE LOAD IS APPLIED IN 2 STEPS
TIMEFUNCTION
0  0
2  1
*
TOL T=E I=15 DN=.00001
*NODES ONLY USED FOR GENERATION ARE FIXED, THE BOTTOM RIGHT HAND
*NODE OF THE HEADER IS FIXED
BOUNDARIES 111111 TYPE=NODES /200 209 75
*THE NODES ON THE RIGHT HAND SIDE OF THE HEADER ARE CONSTRAINED TO
*ROLL ONLY IN THE Z DIRECTION
BOUNDARIES 110111 TYPE=NODES / 50 101 STEP 1 TO 105 6
BOUNDARIES 110111 TYPE=NODES / 148 156 163 170 177 185 192
*THE CONTACT SURFACE IS DEFINED
CGROUP 1 CONTACT2 S=AXISYM
CONTACTSURFACE 1
61 155 162 169 176 184 191 198 72
CONTACTSURFACE 2
87 56 71 52 48 45 42 38 34 31 61
CONTACTPAIR 1 T=2 C=1 F=0
*THE INTERNAL PRESSURE LOADING
LOADS ELEMENT
1 -1 700
STEP 1 TO
10 -1 700
1  2 700
13 2 700
12 2 700
11 2 700
21 2 700
20 2 700
*THE LONGITUDINAL TUBE LOAD
LOADS CONCENTRATED
85 3 -25.3
59 3 -101.3
87 3 -25.3
*THE THERMAL LOAD
LOADS  TEMP TR=0
50   350.0
101  348.1833333
102  346.3666667
103  344.55
104  342.7333333
105  340.9166667
```

```
6     339.1
148   327.9625
156   316.825
163   305.6875
170   294.55
177   283.4125
185   272.275
192   261.1375
75    250
1     350
7     350
10    350
13    350
16    350
19    350
37    350
23    350
26    350
29    350
60    350
33    350
36    350
41    350
44    350
47    350
51    350
54    350
70    350
58    350
85    350
2     350
3     350
62    350
63    350
64    350
65    350
66    350
100   350
113   350
112   350
111   350
```

```
DATAB CREATE
*INPUT FOR THE FINE MESH, 2-DIMENSIONAL AXISYMMETRIC MODEL
HEAD 'HEADER'
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=WAIT PLOTS=NO
*COORDINATES ARE DEFINED
COORDINATES / ENTRIES NODE  X     Y             Z
                      1     0     .63           3.0
                      3     0     .693          3.0
                      37    0     .63           2.844
                      39    0     .75           2.844
                      60    0     .63           2.782
                      61    0     .75           2.782
                      70    0     .63           1.0
                      71    0     .75           1.0
                      72    0     .75001        1.0
                      85    0     .63           0.0
                      87    0     .75           0.0
                      100   0     .938          3.0
                      200   0     .82           2.837
                      152   0     .938          2.97333333
                      256   0     .901          2.88
                      248   0     .792          2.844
```

```
                              251   0     .813           2.969
                              126   0     .938           2.98666666
                              178   0     .938           2.96
                              250   0     .813           2.844
                              246   0     .771           2.844
                              50    0     1.0            3.0
                              6     0     1.0            2.782
                              75    0     1.0            1.0
                              113   0     .938           2.99333333
                              139   0     .938           2.98
                              165   0     .938           2.96666666
                              249   0     .8025          2.844
                              247   0     .7815          2.844
                              245   0     .7605          2.844
*MATERIAL PROPERTIES ARE DEFINED
MATERIAL 1 ELASTIC E=29600000 NU=.3
*THE ELEMENT IS DEFINED
EGROUP 1 PLANE SU=AXISYMM
*THE MESH FOR THE TUBE IS GENERATED
GSURFACE 3 1 37 39 EL1=2 EL2=6 NO=9
GSURFACE 39 37 60 61 EL1=2 EL2=4 NO=9
GSURFACE 61 60 70 71 EL1=2 EL2=8 NO=9
GSURFACE 71 70 85 87 EL1=2 EL2=2 NO=9
*NODES FOR THE WELD ARE GENERATED
LINE A 3 100 NCENTER=200 EL=6 M=1
LINE N 100 178 113 126 139 152 165
LINE A 178 256 NCENTER=251 EL=3 M=1
LINE C 100 256 178
LINE A 256 250 NCENTER=251 EL=3 M=1
LINE N 250 39 249 248 247 246 245
LINE C 256 39 250
*THE MESH FOR THE WELD IS GENERATED
GSURFACE 100 3 39 256 EL1=6 EL2=6 NO=9
*NODES FOR THE HEADER ARE GENERATED
LINE C 100 39 178 256 250
LINE S 50 6 EL=6 M=1
LINE S 6 61 EL=6 M=1

LINE C 50 61 6
*THE MESH FOR THE HEADER IS GENERATED
GSURFACE 50 100 39 61 EL1=4 EL2=12 NO=9
GSURFACE 6 61 72 75 EL1=6 EL2=8 NO=9 NC=N
*PORTIONS OF THE TUBE ARE DEFINED~~ FOR PLOTTING~~
EZONE TUBE01
1 STEP 1 TO 12
EZONE TUBE02
13 STEP 1 TO 44
EZONE WELD
45 STEP 1 TO 80
EZONE HEAD
81 STEP 1 TO 256
BZONE CLOSE XMIN=0 XMAX=0 YMIN=.63 YMAX=1.094 ZMIN=2.688 ZMAX=3.1
BZONE HEAD01 XMIN=0 XMAX=0 YMIN=1.094 YMAX=2.0 ZMIN=2.688 ZMAX=3.0
BZONE HEAD02 XMIN=0 XMAX=0 YMIN=1.094 YMAX=2.0 ZMIN=1.0 ZMAX=2.688
BZONE HEAD03 XMIN=0 XMAX=0 YMIN=.63 YMAX=1.094 ZMIN=1.0 ZMAX=2.688
BZONE TUBE XMIN=0 XMAX=0 YMIN=.63 YMAX=.693 ZMIN=0 ZMAX=1.0
*THE MASTER DEGREES OF FREEDOM ARE DEFINED
MASTER REACTIONS=YES IDOF=100111 DT=1 NSTEP=2
PRINTOUT MAX
ANALYSIS TYPE=STATIC
*THE LOAD IS APPLIED IN 2 STEPS
TIMEFUNCTION
0   0
2   1
*
TOL T=E I=15 DN=.00001
*NODES USED FOR GENERATION ARE FIXED, THE BOTTOM RIGHT HAND NODE
*OF THE HEADER IS FIXED
BOUNDARIES 111111 TYPE=NODES / 200 251 75
```

```
*THE NODES AT THE RIGHT HAND SIDE OF THE HEADER ARE CONSTRAINED TO
*ROLL ONLY IN THE Z-DIRECTION
BOUNDARIES 110111 TYPE=NODES/ 50 368 STEP 1 TO 378 6 558 STEP 13 TO 740
*THE CONTACT SURFACES ARE DEFINED
CGROUP 1 CONTACT2 S=AXISYM
CONTACTSURFACE 1
87 210 205 199 71 191 186 181 175 170 164 159 154 148 143 137 132 127 121 116 61
CONTACTSURFACE 2
61 570 583 596 609 622 635 648 661 674 687 700 713 726 739 752 72
CONTACTPAIR 1 T=2 C=1 F=0
*THE INTERNAL PRESSURE LOAD
LOADS ELEMENT
2 -1 700
STEP 2 TO
40 -1 700
2  2 700
1  2 700
41 2 700
STEP 1 TO
46 2 700
77 2 700
STEP 1 TO
80 2 700
*THE LONGITUDINAL TUBE LOAD
LOADS CONCENTRATED
85   3   -12.66666666
217  3   -50.66666666
216  3   -25.33333333
215  3   -50.66666666
87   3   -12.66666666
*THE THERMAL LOAD
LOADS TEMP TR=0
50     350
368    349.0916667
369    348.1833333
370    347.275
371    346.3666667
372    345.4583333
373    344.55
374    343.6416667
375    342.7333333
376    341.825
377    340.9166667
378    340.0083333
6      339.1
558    333.53125
571    327.9625
584    322.39375
597    316.825
610    311.25625
623    305.6875
636    300.11875
649    294.55
662    288.98125
675    283.4125
688    277.84375
701    272.275
714    266.70625
727    261.1375
740    255.56875
75     250
1      350
STEP 1 TO
5      350
218    350
STEP 1 TO
228    350
```

```
100   350
390   350
STEP 1 TO
396   350
50    350
11    350
STEP 5 TO
36    350
43    350
48    350
54    350
59    350
66    350
37    350
78    350
83    350
90    350
95    350
101   350
106   350
111   350
60    350
120   350
125   350
131   350
136   350
142   350
147   350
153   350
158   350
163   350
169   350
174   350
180   350
185   350
190   350
195   350
70    350
204   350
209   350
214   350
85    350
*
```

APPENDIX H. ADINA-IN INPUT FILE FOR THE 3-DIMENSIONAL CONTACT SURFACE

```
*THESE ARE THE CONTACT SURFACES FOR THE 3-DIMENSIONAL MODEL
CGROUP 1 CONTACT3
*CONTACTSURFACE 1 IS THE HEADER AROUND THE INNER TUBE
CONTACTSURFACE 1
 1  123  124  970  969
 2  969  970  982  981
 3  981  982  994  993
 4  993  994   69   68
 5  124  125  971  970
 6  970  971  983  982
 7  982  983  995  994
 8  994  995   70   69
 9  125  126 1021  971
10  971 1021 1029  983
11  983 1029 1037  995
12  995 1037   71   70
13  126  127 1022 1021
14 1021 1022 1030 1029
15 1029 1030 1038 1037
16 1037 1038   72   71
17  127  128 1057 1022
18 1022 1057 1065 1030
19 1030 1065 1073 1038
20 1038 1073   73   72
21  128  129 1058 1057
22 1057 1058 1066 1065
23 1065 1066 1074 1073
24 1073 1074   74   73
25  129  130 1093 1058
26 1058 1093 1101 1066
27 1066 1101 1109 1074
28 1074 1109   75   74
29  130  131 1094 1093
30 1093 1094 1102 1101
31 1101 1102 1110 1109
32 1109 1110   76   75
33  131  132 1129 1094
34 1094 1129 1137 1102
35 1102 1137 1145 1110
36 1110 1145   77   76
37  132   11 1130 1129
38 1129 1130 1138 1137
39 1137 1138 1146 1145
40 1145 1146    6   77
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41   11  122 1161 1130
42 1130 1161 1165 1138
43 1138 1165 1169 1146
44 1146 1169   67    6
45  122  123  969 1161
46 1161  969  981 1165
47 1165  981  993 1169
48 1169  993   68   67
*CONTACTSURFACE 2 IS THE HEADER AROUND THE OUTER TUBE
CONTACTSURFACE 2
 1  585  586 1354 1323
 2 1323 1354 1358 1331
 3 1331 1358 1362 1339
 4 1339 1362  531  530
 5  586  587 1180 1354
 6 1354 1180 1188 1358
 7 1358 1188 1196 1362
 8 1362 1196  532  531
 9  587  588 1181 1180
10 1180 1181 1189 1188
11 1188 1189 1197 1196
12 1196 1197  533  532
13  588  589 1182 1181
14 1181 1182 1190 1189
15 1189 1190 1198 1197
16 1197 1198  534  533
17  589  590 1212 1182
18 1182 1212 1218 1190
19 1190 1218 1224 1198
20 1198 1224  535  534
21  590  591 1213 1212
22 1212 1213 1219 1218
23 1218 1219 1225 1224
24 1224 1225  536  535
25  591  592 1250 1213
26 1213 1250 1258 1219
27 1219 1258 1266 1225
28 1225 1266  537  536
29  592  593 1251 1250
30 1250 1251 1259 1258
31 1258 1259 1267 1266
32 1266 1267  538  537
33  593  594 1286 1251
34 1251 1286 1294 1259
35 1259 1294 1302 1267
36 1267 1302  539  538
37  594  473 1287 1286
38 1286 1287 1295 1294
39 1294 1295 1303 1302
40 1302 1303  468  539
41  473  584 1322 1287
```

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42 1287 1322 1330 1295
43 1295 1330 1338 1303
44 1303 1338  529  468
45  584  585 1323 1322
46 1322 1323 1331 1330
47 1330 1331 1339 1338
48 1338 1339  530  529
*CONTACTSURFACE 3 IS THE INNER TUBE
CONTACTSURFACE 3
1 195 237 238 196
2 237 90 91 238
3 90 297 298 91
4 297 339 340 298
5 339 381 382 340
6 381 68 69 382
7 196 238 239 197
8 238 91 92 239
9 91 298 299 92
10 298 340 341 299
11 340 382 383 341
12 382 69 70 383
13 197 239 240 198
14 239 92 93 240
15 92 299 300 93
16 299 341 342 300
17 341 383 384 342
18 383 70 71 384
19 198 240 241 199
20 240 93 94 241
21 93 300 301 94
22 300 342 343 301
23 342 384 385 343
24 384 71 72 385
25 199 241 242 200
26 241 94 95 242
27 94 301 302 95
28 301 343 344 302
29 343 385 386 344
30 385 72 73 386
31 200 242 243 201
32 242 95 96 243
33 95 302 303 96
34 302 344 345 303
35 344 386 387 345
36 386 73 74 387
37 201 243 244 202
38 243 96 97 244
39 96 303 304 97
40 303 345 346 304
41 345 387 388 346
42 387 74 75 388
43 202 244 245 203
```

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44 244 97 98 245
45 97 304 305 98
46 304 346 347 305
47 346 388 389 347
48 388 75 76 389
49 203 245 246 204
50 245 98 99 246
51 98 305 306 99
52 305 347 348 306
53 347 389 390 348
54 389 76 77 390
55 204 246 235 193
56 246 99 8 235
57 99 306 295 8
58 306 348 337 295
59 348 390 379 337
60 390 77 6 379
61 193 235 236 194
62 235 8 89 236
63 8 295 296 89
64 295 337 338 296
65 337 379 380 338
66 379 6 67 380
67 194 236 237 195
68 236 89 90 237
69 89 296 297 90
70 296 338 339 297
71 338 380 381 339
72 380 67 68 381
*CONTACTSURFACE 4 IS THE OUTER TUBE
CONTACTSURFACE 4
1 657 699 700 658
2 699 552 553 700
3 552 759 760 553
4 759 801 802 760
5 801 843 844 802
6 843 530 531 844
7 658 700 701 659
8 700 553 554 701
9 553 760 761 554
10 760 802 803 761
11 802 844 845 803
12 844 531 532 845
13 659 701 702 660
14 701 554 555 702
15 554 761 762 555
16 761 803 804 762
17 803 845 846 804
18 845 532 533 846
19 660 702 703 661
20 702 555 556 703
21 555 762 763 556
```

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22 762 804 805 763
23 804 846 847 805
24 846 533 534 847
25 661 703 704 662
26 703 556 557 704
27 556 763 764 557
28 763 805 806 764
29 805 847 848 806
30 847 534 535 848
31 662 704 705 663
32 704 557 558 705
33 557 764 765 558
34 764 806 807 765
35 806 848 849 807
36 848 535 536 849
37 663 705 706 664
38 705 558 559 706
39 558 765 766 559
40 765 807 808 766
41 807 849 850 808
42 849 536 537 850
43 664 706 707 665
44 706 559 560 707
45 559 766 767 560
46 766 808 809 767
47 808 850 851 809
48 850 537 538 851
49 665 707 708 666
50 707 560 561 708
51 560 767 768 561
52 767 809 810 768
53 809 851 852 810
54 851 538 539 852
55 666 708 697 655
56 708 561 470 697
57 561 768 757 470
58 768 810 799 757
59 810 852 841 799
60 852 539 468 841
61 655 697 698 656
62 697 470 551 698
63 470 757 758 551
64 757 799 800 758
65 799 841 842 800
66 841 468 529 842
67 656 698 699 657
68 698 551 552 699
69 551 758 759 552
70 758 800 801 759
71 800 842 843 801
72 842 529 530 843
```

APPENDIX I. ADINA-IN INPUT FILE FOR THE 3-DIMENSIONAL PROBLEM

```
DATAB CREATE
HEAD '3D-HEADER'
CONTROL B=4800 SYSTEM=2 DEVICE=2 OPTION=1024
CONTROL PLOTE=WAIT PLOTS=NO
*THE COORDINATES FOR THE INNER TUBE ARE DEFINED
SYSTEM 1 TYPE=CYLINDRICAL X=9.4 Y=1 Z=1.125
COORDINATES /ENTRIES NODE  R       THETA    XL
                     1     .63     0        0
                     2     .75     0        0
                     3     .63     0        .156
                     4     .75     0        .156
                     5     .63     0        .218
                     6     .75     0        .218
                     7     .63     0        2.0
                     8     .75     0        2.0
                     9     .63     0        4.0
                     10    .75     0        4.0
                     11    .75001  0        2.0
LINE CYLINDRICAL 1 1 6 1
LINE CYLINDRICAL 2 2 6 1
LINE CYLINDRICAL 3 3 6 1
LINE CYLINDRICAL 4 4 6 1
LINE CYLINDRICAL 5 5 6 1
LINE CYLINDRICAL 6 6 6 1
LINE CYLINDRICAL 7 7 6 1
LINE CYLINDRICAL 8 8 6 1
LINE CYLINDRICAL 9 9 6 1
LINE CYLINDRICAL 10 10 6 1
LINE CYLINDRICAL 11 11 6 1
*THE MASTER DEGREES OF FREEDOM ARE DEFINED
MASTER REACTIONS=YES IDOF=000111
PRINTOUT V=MIN IO=0
ANALYSIS TYPE=STATIC
VIEW 1 X=1
VIEW 2 X=-1
VIEW 3 Y=1
VIEW 4 Y=-1
VIEW 5 Z=1
VIEW 6 Z=-1
*THE MATERIAL PROPERTIES ARE DEFINED
MATERIAL 1 ELASTIC E=29600000 NU=.3
*THE ELEMENT IS DEFINED
EGROUP 1 SOLID
STRESSTABLE 1 1 2 3 4 5 6 7 8 21
EDATA/ENTRIES EL   TABLE   PRINT
              1    1       YES
              STEP 1 TO
              288  1       YES
*THE MESH FOR THE INNER TUBE IS GENERATED
GVOLUME 10 10 9 9 8 8 7 7 EL1=6 EL2=1 EL3=4 NO=20
GVOLUME 8 8 7 7 6 6 5 5 EL1=6 EL2=1 EL3=4 NO=20
GVOLUME 6 6 5 5 4 4 3 3 EL1=6 EL2=1 EL3=1 NO=20
GVOLUME 4 4 3 3 2 2 1 1 EL1=6 EL2=1 EL3=1 NO=20
*THE COORDINATES FOR THE OUTER TUBE ARE DEFINED
SYSTEM 2 TYPE=CYLINDRICAL X=9.4 Y=3.0 Z=1.125
```

COORDINATES /ENTRIES

NODE	R	THETA	XL
463	.63	0	-.4564
464	.75	0	-.49
465	.63	0	-.09327705
466	.75	0	-.11162873
479	.63	180	-.1036
490	.75	180	-.07
467	.63	0	.218
468	.75	0	.218
469	.63	0	1.64381482
470	.75	0	1.61759259
471	.63	0	4.0
472	.75	0	4.0
473	.75001	0	1.61759041
589	.75001	180	1.94537256
474	.63	30	-.43276688
475	.63	60	-.3682
476	.63	90	-.28
477	.63	120	-.1918
478	.63	150	-.12723312
480	.63	210	-.12723312
481	.63	240	-.1918
482	.63	270	-.28
483	.63	300	-.3682
484	.63	330	-.43276688
485	.75	30	-.46186535
486	.75	60	-.385
487	.75	90	-.28
488	.75	120	-.175
489	.75	150	-.09813465
491	.75	210	-.09813465
492	.75	240	-.175
493	.75	270	-.28
494	.75	300	-.385
495	.75	330	-.46186535
584	.75001	30	1.63954765
585	.75001	60	1.69953594
586	.75001	90	1.78148148
587	.75001	120	1.86342702
588	.75001	150	1.92341531
590	.75001	210	1.92341531
591	.75001	240	1.86342702
592	.75001	270	1.78148148
593	.75001	300	1.69953594
594	.75001	330	1.63954765
496	.63	30	-.08036908
497	.63	60	-.04510387
498	.63	90	.0030693
499	.63	120	.05124247
500	.63	150	.08650768
501	.63	180	.09941564
502	.63	210	.08650768
503	.63	240	.05124247
504	.63	270	.0030693
505	.63	300	-.04510387
506	.63	330	-.08036908
507	.75	30	-.09626212
508	.75	60	-.05427972
509	.75	90	.0030693
510	.75	120	.06041831
511	.75	150	.10240071
512	.75	180	.11776732
513	.75	210	.10240071
514	.75	240	.06041831
515	.75	270	.0030693

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                      516     .75     300       -.05427972
                      517     .75     330       -.09626212
                      540     .63     30        1.66225867
                      541     .63     60        1.71264813
                      542     .63     90        1.78148148
                      543     .63     120       1.85031484
                      544     .63     150       1.9007043
                      545     .63     180       1.91914817
                      546     .63     210       1.9007043
                      547     .63     240       1.85031484
                      548     .63     270       1.78148148
                      549     .63     300       1.71264813
                      550     .63     330       1.66225867
                      551     .75     30        1.63954951
                      552     .75     60        1.69953704
                      553     .75     90        1.78148148
                      554     .75     120       1.86342593
                      555     .75     150       1.92341346
                      556     .75     180       1.94537037
                      557     .75     210       1.92341346
                      558     .75     240       1.86342593
                      559     .75     270       1.78148148
                      560     .75     300       1.69953704
                      561     .75     330       1.63954951
*
LINE NODES 463 463 474 475
           476 STEP 1 TO 484
LINE NODES 464 464 485 486
           487 STEP 1 TO 495
LINE NODES 465 465 496 497
           498 STEP 1 TO 506
LINE NODES 466 466 507 508
           509 STEP 1 TO 517
LINE CYLINDRICAL 467 467 6 1
LINE CYLINDRICAL 468 468 6 1
LINE NODES 469 469 540 541
           542 STEP 1 TO 550
LINE NODES 470 470 551 552
           553 STEP 1 TO 561
LINE CYLINDRICAL 471 471 6 1
LINE CYLINDRICAL 472 472 6 1
LINE NODES 473 473 584 585
           586 STEP 1 TO 594
*THE MESH FOR THE OUTER TUBE IS GENERATED
GVOLUME 472 472 471 471 470 470 469 469 EL1=6 EL2=1 EL3=4 NO=20
GVOLUME 470 470 469 469 468 468 467 467 EL1=6 EL2=1 EL3=4 NO=20
GVOLUME 468 468 467 467 466 466 465 465 EL1=6 EL2=1 EL3=1 NO=20
GVOLUME 466 466 465 465 464 464 463 463 EL1=6 EL2=1 EL3=1 NO=20
*THE COORDINATES FOR THE HEADER AROUND THE TUBES ARE DEFINED
SYSTEM N=3 TYPE=CARTESIAN X=9.4 Y=0 Z=0
COORDINATES / ENTRIES  NODE  X       Y          Z
*INNER TUBE HEADER NODES
                        925   0.0     0.0        0.0
                        926   .156    0.0        0.0
                        927   .218    0.0        0.0
                        928   2.0     0.0        0.0
                        929   0.0     0.0        1.125
                        930   .156    0.0        1.125
                        931   .218    0.0        1.125
                        932   2.0     0.0        1.125
```

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                          933   0.0    0.0         2.25
                          934   .156   0.0         2.25
                          935   .218   0.0         2.25
                          936   2.0    0.0         2.25
                          937   0.0    2.0         0.0
                          938   .156   2.0         0.0
                          939   .218   2.0         0.0
                          940   2.0    2.0         0.0
                          941   0.0    2.0         1.125
                          942   .156   2.0         1.125
                          943   .218   2.0         1.125
                          944   2.0    2.0         1.125
                          945   0.0    2.0         2.25
                          946   .156   2.0         2.25
                          947   .218   2.0         2.25
                          948   2.0    2.0         2.25
*NODES OF THE CENTERS OF THE TUBES FOR MESH GENERATION
                          949   0.0    1.0         1.125
                          950   .156   1.0         1.125
                          951   .218   1.0         1.125
                          952   2.0    1.0         1.125
                          953   0.0    3.0         1.125
                          954   .156   3.0         1.125
                          955   .218   3.0         1.125
                          956   2.0    3.0         1.125
*OUTER TUBE HEADER NODES
                          1230  1.41   4.7         2.25
                          1231  .218   4.2764467   2.25
                          1232  -.171  4.13822335  2.25
                          1233  -.56   4.0         2.25
                          1234  1.41   4.7         1.125
                          1235  .218   4.2764467   1.125
                          1236  -.171  4.13822335  1.125
                          1237  -.56   4.0         1.125
                          1238  1.41   4.7         0.0
                          1239  .218   4.2764467   0.0
                          1240  -.171  4.13822335  0.0
                          1241  -.56   4.0         0.0
*GENERATION OF THE MESH FOR THE INNER TUBE HEADER
LINE NODES 123 125 124
LINE ARC 68 70 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 46 48 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 24 26 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 948 936 125 123 947 935 70 68 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 947 935 70 68 946 934 48 46 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 946 934 48 46 945 933 26 24 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 125 127 126
LINE ARC 70 72 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 48 50 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 26 28 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 936 932 127 125 935 931 72 70 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 935 931 72 70 934 930 50 48 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 934 930 50 48 933 929 28 26 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 127 129 128
LINE ARC 72 74 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 50 52 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 28 30 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 932 928 129 127 931 927 74 72 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 931 927 74 72 930 926 52 50 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 930 926 52 50 929 925 30 28 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 129 131 130
LINE ARC 74 76 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 52 54 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 30 32 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 928 940 131 129 927 939 76 74 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 927 939 76 74 926 938 54 52 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 926 938 54 52 925 937 32 30 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 131 11 132
LINE ARC 76 6 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 54 4 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 32 2 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 940 944 11 131 939 943 6 76 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 939 943 6 76 938 942 4 54 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 938 942 4 54 937 941 2 32 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 11 123 122
LINE ARC 6 68 NCEN=951 EL=1 M=1 NCO=ALL
LINE ARC 4 46 NCEN=950 EL=1 M=1 NCO=ALL
LINE ARC 2 24 NCEN=949 EL=1 M=1 NCO=ALL
GVOLUME 944 948 123 11 943 947 68 6 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 943 947 68 6 942 946 46 4 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 942 946 46 4 941 945 24 2 EL1=1 EL2=1 EL3=1 NC=A
*GENERATION OF THE MESH FOR THE OUTER TUBE HEADER
LINE NODES 587 589 588
LINE NODES 532 534 533
LINE NODES 510 512 511
LINE NODES 488 490 489
GVOLUME 948 944 589 587 947 943 534 532 EL1=1 EL2=1 EL3=4 NC=N
LINE NODES 532 510 891
GVOLUME 947 943 534 532 946 942 512 510 EL1=1 EL2=1 EL3=1 NC=A
LINE NODES 510 488 909
GVOLUME 946 942 512 510 945 941 490 488 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 589 591 590
LINE NODES 534 536 535
LINE NODES 512 514 513
LINE NODES 490 492 491
GVOLUME 944 940 591 589 943 939 536 534 EL1=1 EL2=1 EL3=4 NC=N
LINE NODES 536 514 893
GVOLUME 943 939 536 534 942 938 514 512 EL1=1 EL2=1 EL3=1 NC=A
LINE NODES 514 492 911
GVOLUME 942 938 514 512 941 937 492 490 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 591 593 592
LINE NODES 536 538 537
LINE NODES 514 516 515
LINE NODES 492 494 493
GVOLUME 940 1238 593 591 939 1239 538 536 EL1=1 EL2=1 EL3=4 NC=N
LINE NODES 538 516 894
GVOLUME 939 1239 538 536 938 1240 516 514 EL1=1 EL2=1 EL3=1 NC=A
LINE NODES 516 494 912
GVOLUME 938 1240 516 514 937 1241 494 492 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 593 473 594
LINE NODES 538 468 539
LINE NODES 516 466 517
LINE NODES 494 464 495
GVOLUME 1238 1234 473 593 1239 1235 468 538 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 1239 1235 468 538 1240 1236 466 516 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 1240 1236 466 516 1241 1237 464 494 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 473 585 584
LINE NODES 468 530 529
LINE NODES 466 508 507
LINE NODES 464 486 485
GVOLUME 1234 1230 585 473 1235 1231 530 468 EL1=1 EL2=1 EL3=4 NC=N
LINE NODES 530 508 890
GVOLUME 1235 1231 530 468 1236 1232 508 466 EL1=1 EL2=1 EL3=1 NC=A
LINE NODES 508 486 908
GVOLUME 1236 1232 508 466 1237 1233 486 464 EL1=1 EL2=1 EL3=1 NC=A
*
LINE NODES 585 587 586
LINE NODES 530 532 531
LINE NODES 508 510 509
LINE NODES 486 488 487
GVOLUME 1230 948 587 585 1231 947 532 530 EL1=1 EL2=1 EL3=4 NC=N
GVOLUME 1231 947 532 530 1232 946 510 508 EL1=1 EL2=1 EL3=1 NC=A
GVOLUME 1232 946 510 508 1233 945 488 486 EL1=1 EL2=1 EL3=1 NC=A
*COORDINATES FOR THE REST OF THE HEADER ARE DEFINED
SYSTEM N=0
COORDINATES/ ENTRIES NODE X     Y     Z
                     1366 9.09  6.32  0
                     1367 9.09  6.32  2.25
                     1368 7.86  4.67  0
                     1369 7.86  4.67  2.25
                     1370 6.9   6.79  0
                     1371 6.9   6.79  2.25
                     1372 6.644 4.85  0
                     1373 6.644 4.85  2.25
                     1374 4.91  6.37  0
                     1375 4.91  6.37  2.25
                     1376 5.39  4.6   0
                     1377 5.39  4.6   2.25
                     1378 3.16  5.575 0
                     1379 3.16  5.575 2.25
                     1380 4.3   4.057 0
                     1381 4.3   4.057 2.25
                     1382 1.93  4.61  0
                     1383 1.93  4.61  2.25
                     1384 3.31  3.33  0
                     1385 3.31  3.33  2.25
                     1386 .77   3.03  0
                     1387 .77   3.03  2.25
                     1388 2.53  2.356 0
                     1389 2.53  2.356 2.25
                     1390 .17   1.55  0
                     1391 .17   1.55  2.25
                     1392 2.046 1.22  0
                     1393 2.046 1.22  2.25
                     1394 0     0     0
                     1395 0     0     2.25
                     1396 1.87  0     0
                     1397 1.87  0     2.25
                     1398 8.27  5.22  0
                     1399 8.27  5.22  2.25
                     1400 8.065 4.945 0
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                        1401  8.065 4.945 2.25
*THE MESH FOR THE REST OF THE HEADER IS GENERATED
GVOLUME 1238 1230 1231 1239 1366 1367 1399 1398 EL1=2 EL2=4 EL3=1
GVOLUME 1239 1231 1232 1240 1398 1399 1401 1400 EL1=2 EL2=1 EL3=1
GVOLUME 1240 1232 1233 1241 1400 1401 1369 1368 EL1=2 EL2=1 EL3=1
GVOLUME 1367 1366 1370 1371 1369 1368 1372 1373 EL1=2 EL2=1 EL3=6
GVOLUME 1371 1370 1374 1375 1373 1372 1376 1377 EL1=2 EL2=1 EL3=6
GVOLUME 1375 1374 1378 1379 1377 1376 1380 1381 EL1=2 EL2=1 EL3=6
GVOLUME 1379 1378 1382 1383 1381 1380 1384 1385 EL1=2 EL2=1 EL3=6
GVOLUME 1383 1382 1386 1387 1385 1384 1388 1389 EL1=2 EL2=1 EL3=6
GVOLUME 1387 1386 1390 1391 1389 1388 1392 1393 EL1=2 EL2=1 EL3=6
GVOLUME 1391 1390 1394 1395 1393 1392 1396 1397 EL1=2 EL2=1 EL3=6
*THE NODES AT THE CENTER OF THE TUBES ARE FIXED
BOUNDARIES 111111 TYPE=NODES/949 STEP 1 TO 956
*THE NODE AT THE ORIGIN IS FIXED
BOUNDARIES 111111 TYPE=NODES/1892
*THE NODES ABOVE THE ORIGIN ARE ONLY ALLOWED TO ROLL IN THE X-DIRECTION
BOUNDARIES 011111 TYPE=NODES
 932 1015 1018 1023 1026 1031 1034 1039 931 1043 930 1046 929
 1895 1902 1906 1913 1917 1924 1928 1935 1939 1946 1950 1956
*THE NODES IN THE Y=0 PLANE ARE CONSTRAINED TO ROLL ONLY IN THAT PLANE
BOUNDARIES 010111 TYPE=NODES
 936 1013 1049 928 961 1051 966 1017 1053 1054 973 1059 978 1025 1061 1062
 985 1067 990 1033 1069 1070 997 1075 935 1041 1077 927 1004 1079 934 1044
 1080 926 1009 1082 933 1047 1083 925 1394 1395 1891 1893 1894 1896 1900
 1901 1903 1904 1905 1907 1911 1912 1914 1915 1916 1918 1922 1923 1925 1926
 1927 1929 1933 1934 1936 1937 1938 1940 1944 1945 1947 1948 1949 1951 1396
 1397 1955 1957
*THE NODES IN THE Z=0 PLANE ARE CONSTRAINED TO ROLL ONLY IN THAT PLANE
BOUNDARIES 001111 TYPE=NODES
    1    2    3    4    5    6    7    8    9   10   11   17   28   39   50
   61   72   83   94  105  116  127  133  136  139  142  145  148  151  157
  163  166  169  175  181  184  187  190  193  199  205  208  211  217  223
  226  229  232  235  241  247  250  253  259  265  268  271  274  277  280
  283  286  289  292  295  301  307  310  313  319  325  328  331  334  337
  343  349  352  355  361  367  370  373  376  379  385  391  394  397  403
  409  412  415  418  421  424  427  430  433  436  439  442  445  448  451
  454  457  460  463  464  465  466  467  468  469  470  471  472  473  479
  490  501  512  523  534  545  556  567  578  589  595  598  601  604  607
  610  613  619  625  628  631  637  643  646  649  652  655  661  667  670
  673  679  685  688  691  694  697  703  709  712  715  721  727  730  733
  736  739  742  745  748  751  754  757  763  769  772  775  781  787  790
  793  796  799  805  811  814  817  823  829  832  835  838  841  847  853
  856  859  865  871  874  877  880  883  886  889  892  895  898  901  904
  907  910  913  916  919  922  941  942  943  944
 1014 1016 1020 1022 1024 1028 1030 1032 1036 1038 1040 1042
 1045 1048 1055 1063 1071 1122 1123 1124 1126 1128 1130 1131 1132 1134 1136
 1138 1139 1140 1142 1144 1146 1147 1148 1150 1151 1153 1154 1156 1159 1163
 1167 1174 1176 1179 1182 1184 1187 1190 1192 1195 1198 1200 1202 1204 1206
 1210 1216 1222 1234 1235 1236 1237 1279 1280 1281 1283 1285 1287 1288 1289
 1291 1293 1295 1296 1297 1299 1301 1303 1304 1305 1307 1308 1310 1311 1313
 1320 1328 1336 1403 1406 1409 1412 1415 1418 1421 1425 1429 1433 1437 1441
 1445 1448 1451 1454 1457 1460 1463 1466 1469 1472 1475 1478 1482 1486 1489
 1493 1497 1500 1504 1508 1511 1515 1519 1522 1526 1530 1533 1536 1539 1542
 1545 1548 1552 1556 1559 1563 1567 1570 1574 1578 1581 1585 1589 1592 1596
 1600 1603 1606 1609 1612 1615 1618 1622 1626 1629 1633 1637 1640 1644 1648
 1651 1655 1659 1662 1666 1670 1673 1676 1679 1682 1685 1688 1692 1696 1699
 1703 1707 1710 1714 1718 1721 1725 1729 1732 1736 1740 1743 1746 1749 1752
 1755 1758 1762 1766 1769 1773 1777 1780 1784 1788 1791 1795 1799 1802 1806
 1810 1813 1816 1819 1822 1825 1828 1832 1836 1839 1843 1847 1850 1854 1858
 1861 1865 1869 1872 1876 1880 1883 1886 1889 1898 1909 1920 1931 1942 1953
*THE INTERNAL PRESSURE LOAD IS APPLIED
LOADS ELEMENT
1 -2 700
STEP 1 TO
120 -2 700
55 -3 700
STEP 1 TO
60 -3 700
115 -3 700
STEP 1 TO
120 -3 700
126 -3 700
STEP 6 TO
192 -3 700
203 -2 700
204 -2 700
215 -3 700
STEP 12 TO
287 -3 700
216 -3 700
STEP 12 TO
288 -3 700
*
CONSTRAINTS
*THE FOLLOWING CONSTRAINTS ARE NECESSARY BECAUSE COORDINATES WERE
*DUPLICATED IN THE GENERATION OF THE MESH FOR THE HEADER AT THE
*BOUNDARY OF THE TUBES
968 1 1019 1
968 2 1019 2
968 3 1019 3
1020 1 1055 1
1020 2 1055 2
1056 1 1091 1
1056 2 1091 2
1056 3 1091 3
1127 1 1092 1
1127 2 1092 2
1127 3 1092 3
1159 1 1128 1
1159 2 1128 2
967 1 1160 1
967 2 1160 2
967 3 1160 3
980 1 1027 1
980 2 1027 2
980 3 1027 3
1028 1 1063 1
1028 2 1063 2
1064 1 1099 1
1064 2 1099 2
1064 3 1099 3
1135 1 1100 1
1135 2 1100 2
1135 3 1100 3
1163 1 1136 1
1163 2 1136 2
979 1 1164 1
979 2 1164 2
979 3 1164 3
```

```
992 1 1035 1
992 2 1035 2
992 3 1035 3
1036 1 1071 1
1036 2 1071 2
1072 1 1107 1
1072 2 1107 2
1072 3 1107 3
1143 1 1108 1
1143 2 1108 2
1143 3 1108 3
1167 1 1144 1
1167 2 1144 2
991 1 1168 1
991 2 1168 2
991 3 1168 3
1158 1 1177 1
1158 2 1177 2
1158 3 1177 3
1179 1 1210 1
1179 2 1210 2
1125 1 1209 1
1125 2 1209 2
1125 3 1209 3
1211 1 1248 1
1211 2 1248 2
1211 3 1248 3
1284 1 1249 1
1284 2 1249 2
1284 3 1249 3
1320 1 1285 1
1320 2 1285 2
1352 1 1321 1
1352 2 1321 2
1352 3 1321 3
1178 1 1353 1
1178 2 1353 2
1178 3 1353 3
1162 1 1185 1
1162 2 1185 2
1162 3 1185 3
1187 1 1216 1
1187 2 1216 2
1133 1 1215 1
1133 2 1215 2
1133 3 1215 3
1217 1 1256 1
1217 2 1256 2
1217 3 1256 3
1292 1 1257 1
1292 2 1257 2
1292 3 1257 3
1328 1 1293 1
1328 2 1293 2
1356 1 1329 1
1356 2 1329 2
1356 3 1329 3
1186 1 1357 1
1186 2 1357 2
1186 3 1357 3
```

```
1166 1 1193 1
1166 2 1193 2
1166 3 1193 3
1195 1 1222 1
1195 2 1222 2
1141 1 1221 1
1141 2 1221 2
1141 3 1221 3
1223 1 1264 1
1223 2 1264 2
1223 3 1264 3
1300 1 1265 1
1300 2 1265 2
1300 3 1265 3
1336 1 1301 1
1336 2 1301 2
1360 1 1337 1
1360 2 1337 2
1360 3 1337 3
1194 1 1361 1
1194 2 1361 2
1194 3 1361 3
*THE FOLLOWING CONSTRAINTS DEFINE THE CONTACT SURFACES
 585 2  552 2
 585 3  552 3
 586 2  553 2
 586 3  553 3
 587 2  554 2
 587 3  554 3
 588 2  555 2
 588 3  555 3
 589 2  556 2
 590 2  557 2
 590 3  557 3
 591 2  558 2
 591 3  558 3
 592 2  559 2
 592 3  559 3
 593 2  560 2
 593 3  560 3
 594 2  561 2
 594 3  561 3
 473 2  470 2
 584 2  551 2
 584 3  551 3
1323 2  759 2
1323 3  759 3
1354 2  760 2
1354 3  760 3
1180 2  761 2
1180 3  761 3
1181 2  762 2
1181 3  762 3
1182 2  763 2
1212 2  764 2
1212 3  764 3
1213 2  765 2
1213 3  765 3
1250 2  766 2
1250 3  766 3
```

```
1251 2  767 2
1251 3  767 3
1286 2  768 2
1286 3  768 3
1287 2  757 2
1322 2  758 2
1322 3  758 3
1331 2  801 2
1331 3  801 3
1358 2  802 2
1358 3  802 3
1188 2  803 2
1188 3  803 3
1189 2  804 2
1189 3  804 3
1190 2  805 2
1218 2  806 2
1218 3  806 3
1219 2  807 2
1219 3  807 3
1258 2  808 2
1258 3  808 3
1259 2  809 2
1259 3  809 3
1294 2  810 2
1294 3  810 3
1295 2  799 2
1330 2  800 2
1330 3  800 3
1339 2  843 2
1339 3  843 3
1362 2  844 2
1362 3  844 3
1196 2  845 2
1196 3  845 3
1197 2  846 2
1197 3  846 3
1198 2  847 2
1224 2  848 2
1224 3  848 3
1225 2  849 2
1225 3  849 3
1266 2  850 2
1266 3  850 3
1267 2  851 2
1267 3  851 3
1302 2  852 2
1302 3  852 3
1303 2  841 2
1338 2  842 2
1338 3  842 3
 123 2   90 2
 123 3   90 3
 124 2   91 2
 124 3   91 3
 125 2   92 2
 125 3   92 3
 126 2   93 2
 126 3   93 3
 127 2   94 2
 128 2   95 2
 128 3   95 3
 129 2   96 2
 129 3   96 3
 130 2   97 2
 130 3   97 3
 131 2   98 2
 131 3   98 3
 132 2   99 2
 132 3   99 3
  11 2    8 2
 122 2   89 2
 122 3   89 3
 969 2  297 2
 969 3  297 3
 970 2  298 2
 970 3  298 3
 971 2  299 2
 971 3  299 3
1021 2  300 2
1021 3  300 3
1022 2  301 2
1057 2  302 2
1057 3  302 3
1058 2  303 2
1058 3  303 3
1093 2  304 2
1093 3  304 3
1094 2  305 2
1094 3  305 3
1129 2  306 2
1129 3  306 3
1130 2  295 2
1161 2  296 2
1161 3  296 3
 981 2  339 2
 981 3  339 3
 982 2  340 2
 982 3  340 3
 983 2  341 2
 983 3  341 3
1029 2  342 2
1029 3  342 3
1030 2  343 2
1065 2  344 2
1065 3  344 3
1066 2  345 2
1066 3  345 3
1101 2  346 2
1101 3  346 3
1102 2  347 2
1102 3  347 3
1137 2  348 2
1137 3  348 3
1138 2  337 2
1165 2  338 2
1165 3  338 3
 993 2  381 2
 993 3  381 3
 994 2  382 2
 994 3  382 3
 995 2  383 2
 995 3  383 3
1037 2  384 2
1037 3  384 3
1038 2  385 2
1073 2  386 2
1073 3  386 3
1074 2  387 2
1074 3  387 3
1109 2  388 2
1109 3  388 3
1110 2  389 2
1110 3  389 3
1145 2  390 2
1145 3  390 3
1146 2  379 2
1169 2  380 2
1169 3  380 3
 283 2 1124 2
 284 2  962 2
 284 3  962 3
 285 2  963 2
 285 3  963 3
 286 2 1016 2
 287 2 1052 2
 287 3 1052 3
 288 2 1088 2
 288 3 1088 3
 325 2 1132 2
 326 2  974 2
 326 3  974 3
 327 2  975 2
 327 3  975 3
 328 2 1024 2
 329 2 1060 2
 329 3 1060 3
 330 2 1096 2
 330 3 1096 3
 367 2 1140 2
 368 2  986 2
 368 3  986 3
 369 2  987 2
 369 3  987 3
 370 2 1032 2
 371 2 1068 2
 371 3 1068 3
 372 2 1104 2
 372 3 1104 3
 409 2 1148 2
 410 2  998 2
 410 3  998 3
 411 2  999 2
 411 3  999 3
 412 2 1040 2
 413 2 1076 2
 413 3 1076 3
 414 2 1112 2
 414 3 1112 3
 745 2 1281 2
```

```
  746 2 1317 2
  746 3 1317 3
  747 2 1175 2
  747 3 1175 3
  748 2 1176 2
  749 2 1208 2
  749 3 1208 3
  750 2 1245 2
  750 3 1245 3
  787 2 1289 2
  788 2 1325 2
  788 3 1325 3
  789 2 1183 2
  789 3 1183 3
  790 2 1184 2
  791 2 1214 2
  791 3 1214 3
  792 2 1253 2
  792 3 1253 3
  829 2 1297 2
  830 2 1333 2
  830 3 1333 3
  831 2 1191 2
  831 3 1191 3
  832 2 1192 2
  833 2 1220 2
  833 3 1220 3
  834 2 1261 2
  834 3 1261 3
  871 2 1305 2
  872 2 1341 2
  872 3 1341 3
  873 2 1199 2
  873 3 1199 3
  874 2 1200 2
  875 2 1226 2
  875 3 1226 3
  876 2 1269 2
  876 3 1269 3
*PORTIONS OF THE MODEL ARE DEFINED FOR GRAPHICS
EZONE TUBE1
1 2 STEP 1 TO 60
EZONE TUBE2
61 62 STEP 1 TO 120
EZONE TUBE3
121 122 STEP 1 TO 156
EZONE TUBE4
157 158 STEP 1 TO 192
ZZONE COMBO1 TUBE1 TUBE3
ZZONE COMBO2 TUBE2 TUBE4
ZZONE COMBO3 TUBE1 TUBE2 TUBE3 TUBE4
EZONE LOAD
126 STEP 6 TO 192 203 STEP 12 TO 287 204 STEP 12 TO 288
ZZONE LOADING TUBE1 TUBE2 LOAD
```

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